

by Baohong Hou^{1,2}, Bernd H Michaelsen², Ziyang Li³, John L Keeling², Adrian J Fabris² and IGCP-514 participants

Paleovalley-related uranium: exploration criteria and case-studies from Australia and China

1 College of Earth Science, Jilin University, Jilin, P. R. China

2 Geological Survey of South Australia (DMITRE), Adelaide, Australia; E-mail: baohong.hou@sa.gov.au

3 Beijing Research Institute of Uranium Geology (BRIUG), CNNC, Beijing, P. R. China

Uranium exploration and mining in Australia and China are significant and increasingly important sectors of each country's respective mineral industry. Here we focus on similarities in the geology of paleovalley-related uranium mineralising systems, which can be used to refine strategies for exploration. Paleovalley-related uranium resources are developed as sandstone-hosted and surficial deposits within paleovalley-fills, deposited either on incised crystalline bedrock, or incised sedimentary cover that is often of similar age to the sediments that host the mineralisation. With respect to Sino-Australian examples, paleovalley-related uranium occurs mostly around the margins of Mesozoic and Cenozoic basins; often the mineralisation is hosted within sands contained within paleovalleys developed upon, or proximal to, Precambrian crystalline rock that contains primary uranium mineralisation. Numerous examples are known in Australia and China where granitic rocks of pre-Mesozoic age contain uranium in the range 10–100 ppm, concentrations significantly above the crustal average of 2.8 ppm uranium. Crystalline rocks with above-background levels of uranium that are incised by paleovalleys are often the inferred source of the sandstone-hosted uranium. In these regions, extensive fluvial systems developed particularly during Mesozoic and early Cenozoic times, eroded weathered basement rocks to physically disperse uranium into the cover sediments, with subsequent chemical remobilisation, dispersion and concentration of uranium occurring throughout the late Cenozoic.

Paleovalley-related uranium deposits are typically hosted within unlithified sand, lignitic clays or calcreted channel-fill, deposited in continental or marginal marine environments. Sandstone-hosted uranium deposits in many cases contain impermeable clay layers, intercalated within the sedimentary sequence; impervious

layers often form the upper and lower bounding strata of individual deposits. Uranium deposits are associated with reduced lithologies; mineralisation is developed where oxidising fluids (carrying dissolved U) were modified by interaction with reduced sands, the latter commonly containing pyrite and dispersed organic matter and/or seams of lignite. Mineralised bodies, often tabular or roll-shaped, formed along the interface between clay horizons and the sandy facies of paleovalley sediments. Geological, geophysical and geochemical features of the paleovalleys and related uranium deposits have been used to construct models to understand ore genesis and assist exploration for paleovalley-hosted uranium deposits.

Australia and China remain highly prospective for the discovery of new paleovalley-related uranium deposits. The precise geometric definitions of the basin margin and paleovalley architecture are important in identifying exploration targets and improving the effectiveness of drilling. This requires the integration of various geoscientific data sets. Refinements in remote sensing, geophysical techniques and data processing, in combination with sedimentological and depositional interpretations, provide an efficient approach for outlining the principal drainage patterns and channel dimensions. To help reduce risk, an exploration strategy should combine these technologies with a detailed understanding of the physicochemical parameters of uranium reduction, mobilisation and preservation.

Introduction

Uranium occurs in various geological settings, within igneous, hydrothermal and sedimentary environments. World-wide, uranium deposits have been grouped into 14 major categories based on their host-rock type and geological setting (OECD/NEA & IAEA, 2000). The major types of these uranium deposits and their economic

significance in Australia, China and world-wide are summarized in Table 1. The geographic distribution of Australian and Chinese uranium resources are shown in Figure 1. World-wide exploration for paleovalley-related uranium deposits is focused mainly on Mesozoic and Cenozoic sediments adjacent to Archean-Proterozoic cratons containing uranium-enriched igneous rocks (e.g., Gawler and Curnamona Provinces of South Australia, Yilgarn Craton of Western Australia; Curtis et al., 1990; northern China Platform and cratons in the Qilian-Qinling and Tianshan Provinces of China; Zhang and Li, 2008).

Historically, most discoveries are made during periods of increased exploration (Yates and Randell, 1994, McKay and Mieztis, 2001). The post-2005 renewed interest in uranium exploration, targeting Cenozoic and Mesozoic sediments in Australia and China, reflects several drivers: an increase in demand for uranium as an alternative to burning fossil fuels - particularly in China, the vast areas of Mesozoic and Cenozoic sediments with high potential to host uranium, a proactive government policy for uranium development, and recent success with discovery of new high-grade mineralisation in South Australia (e.g. Paralana uranium field comprising Four Mile and Pepegooona deposits) (Figs. 1a and 2) and northern China (e.g. Dongsheng deposits in the Ordos Basin) (Fig. 1).

Significant paleovalley-related uranium resource and potential exist in Australia and China where uranium exploration and mining constitute an important and growing part of each nation's mineral and energy economy. Recent discoveries of paleovalley-related uranium mineralisation (e.g. Theseus deposit in a Cenozoic paleovalley of Western Australia, Afghan Swan deposit in the Ngalia Basin (Northern Territory), Blackbush deposit in the Pirie Basin, and the Four Mile East and Pepegooona deposits near the margin of the Callabonna Sub-basin of South Australia (Figs. 1a and 2); and the Turpan-Hami deposits of Xinjiang Province, Dongsheng deposits in the Ordos Basin and Qianjiadian deposits in Songliao Basin of northern China, for instance, highlight the potential prospectivity of both greenfield and brownfield regions in each country (Fig. 1). Paleovalley-related uranium deposits contain around 40% of the world's uranium deposits (e.g. sandstone uranium 37.5% and surficial uranium 4%; IAEA, 2009). Significant resources within these styles of deposits have been identified in Mesozoic and Cenozoic sediments within fluvial and marginal marine environments in Australia and northern China (Figs. 1 and 2).

In the Australian examples, uranium mineralisation occurs nearly entirely within Cenozoic sedimentary basins flanking or overlying Proterozoic rocks that are enriched in uranium (e.g., Gawler Craton and Curnamona Province; Table 1) (Hou et al., 2007a). By contrast, in China, uranium mineralisation occurs mainly in Mesozoic basins flanking or overlying pre-Jurassic rocks known to be enriched in uranium (e.g., Ordos and Songliao Basins) (Zhang and Li, 2008). Major uranium resources of similar style also occur in USA, Niger, Kazakhstan, Uzbekistan, Gabon (Franceville Basin), and South Africa (Karoo Basin). Worldwide, paleovalley-related sediments have yielded and will continue to yield uranium from medium-grade deposits at relatively low cost (McKay and Mieztis, 2001).

Examples of paleovalley-related uranium deposits throughout the world, such as in Australia, China, USA and Kazakhstan, are often within paleovalleys and associated sediments deposited in fluvio-deltaic paralic environments. The development of these sedimentary ores is the result of a combination of factors including sediment permeability, presence of reductant (e.g., organic matter), proximity

to uranium bedrock source regions, and favourable groundwater flow. Both Australia and China currently have significant undeveloped resources in paleovalley-related uranium deposits and ongoing exploration has led to recent new discoveries.

This paper outlines the geology and characteristics of paleovalley-related uranium deposits and exploration criteria, based largely on case studies deriving from various research projects under the banner of **International Geological Correlation Project IGCP 514: Fluvial paleosystems – evolution and mineral deposits**, which aims to support uranium explorers in area selection at regional and local scales. We also provide revised conceptual models and key exploration criteria for paleovalley-related uranium systems within Australia and China.

Paleovalley-related uranium deposits

Fluvial paleosystems are developed within topographic features that define host paleovalleys. Recognition of these features in the present-day landscape is important in establishing physical links to primary uranium source rocks and in determining the pattern of groundwater flow at the time of uranium deposition. In the context of this paper, 'paleovalley-related' uranium deposits encompass three categories (Table 1) including variants of 'sandstone-hosted' deposits, lignite-type deposits, and surficial deposits of the 'calcrete' type (Fig. 3) (Hou et al., 2007b). The term 'paleovalley-related' implies more than just uranium hosted within sediments confined to the paleo-valley proper. The various styles of uranium mineralisation associated with these systems can include any diagenetic/epigenetic concentration of uranium minerals occurring in fluvial, alluvial, lacustrine, and estuarine sediments. Cenozoic paleovalleys of Australia, and Mesozoic paleovalleys of China host the greatest number of uranium deposits and include the largest and highest grade deposits of these styles of sedimentary uranium mineralisation. For example, the Callabonna Sub-basin in South Australia, is a richly endowed fluvial and lacustrine

Table 1. Types of uranium deposits. Numbers represent the approximate economic Australia significance of the seven most important deposit types while numbers in brackets represent the approximate economic worldwide significance of the seven most important deposit types (from McKay and Mieztis, 2001; OECD/NEA and IAEA, 2012; Zhang and Li, 2008).

Types of uranium deposits	Ranking of importance (contained U ₃ O ₈) with respect to country		
	Australia	China	Worldwide*
Breccia complex deposits (3)	1		2
Unconformity-related deposits (1)	2		3
Sandstone deposits (2)	3	3	1
Surficial deposits (6)	4		6
Metasomatite deposits (7)	5	~7	7
Metamorphic deposits	6		
Volcanic deposits	7	2	
Intrusive deposits (5)	8	1	5
Vein deposits	9	4	
Quartz-pebble conglomerate deposits (4)	10	-	4
Collapse breccia pipe deposits	11	-	
Phosphorite deposits	12	8	
Lignite	13	~6	
Black shale deposits	14	~5	

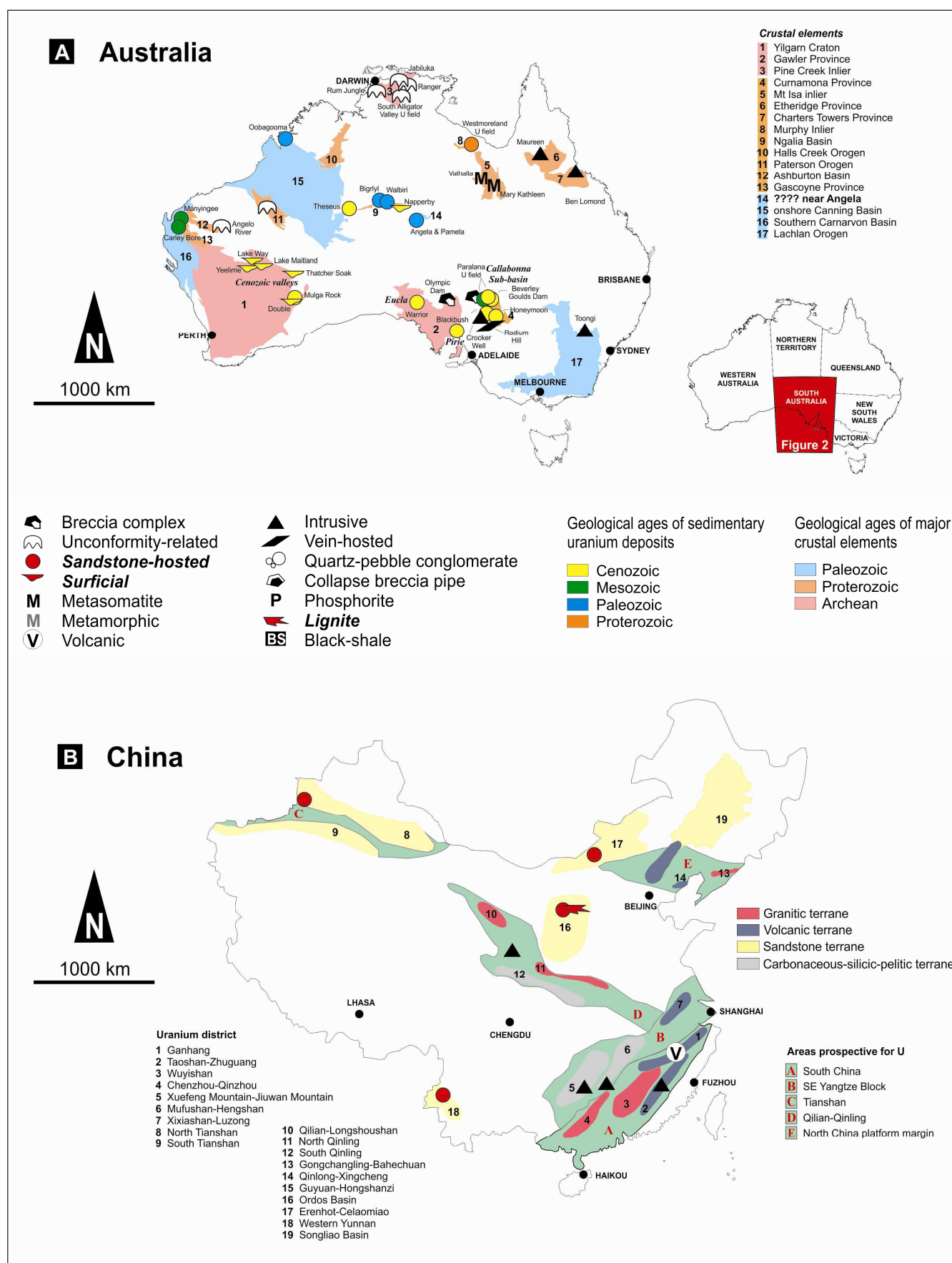


Figure 1. Main uranium deposits/metallogenic regions in (A) Australia and (B) China (modified from Kreuzer et al., 2010; Zhang and Li, 2008).

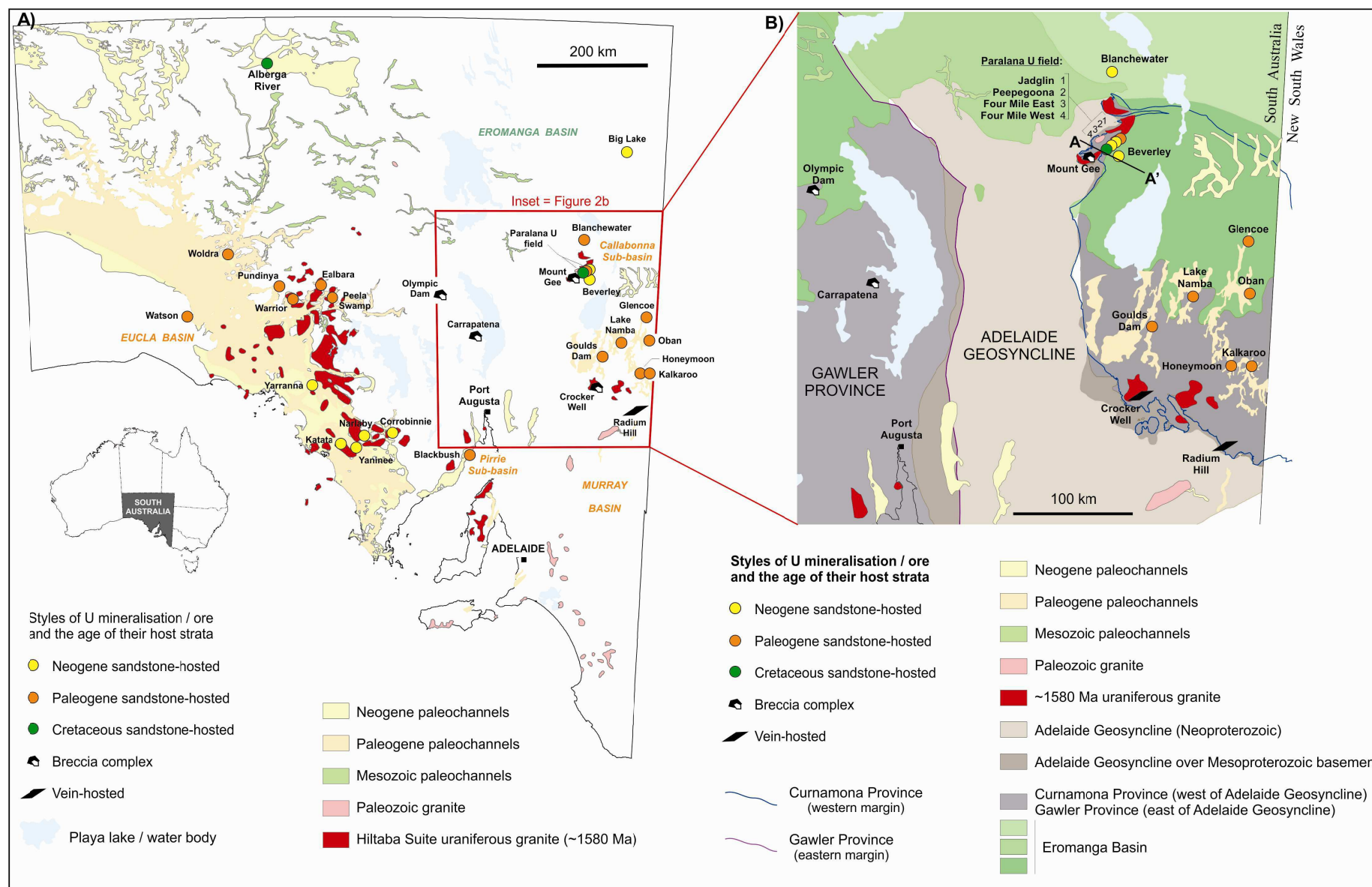


Figure 2. (a). Major paleovalleys and related uranium deposits of South Australia (after Hou et al. 2013), also showing exposed paleozoic and uraniferous Hiltaba Suite granite (~1580 Ma) and equivalents; **(b).** Northern Flinders Ranges district, South Australia showing the distribution of sandstone-hosted uranium mineralisation, delineated paleochannels (after Hou et al. 2013), and exposed Paleozoic and uraniferous Hiltaba Suite granites (~1580 Ma) and equivalents.

continental basin, with resources in excess of 62.4 kt U_3O_8 , being 38% of Australia's sandstone-hosted resource inventory (Penney, 2012).

Source rocks

The distribution of known uranium resources shows a clear spatial relationship with uranium-enriched bedrock in Australia (Lambert et al., 2005) and China (Zhang and Li., 2008). The location of deposits is strongly influenced by the presence of Mesoproterozoic and Archean uranium-rich source rocks in the headwaters of paleovalleys draining into Mesozoic and Cenozoic basins developed in Australia (e.g., Northern Territory, Western Australia and South Australia) (Figs. 1 and 2) and China (e.g., Tianshan region, Ordos Basin and Songliao Basin, northern China) (Fig. 1). In Australia, significant uraniferous igneous rocks (containing >10 ppm uranium) formed during the Proterozoic and are widespread throughout South Australia, the Northern Territory, Western Australia and parts of Queensland. The distribution of anomalously high uranium-bearing granites is correlated also with areas of high geothermal gradient (Lambert et al., 2005). For example, paleovalley-related uranium deposits within the Callabonna Sub-basin of South Australia occur proximal to highlands of Proterozoic rock containing significant uranium enrichment (i.e., the Mount Painter Inlier, northwestern Curnamona Province) (Fig. 2) (Hou et al., 2006). South Australia's Gawler Craton and Western Australia's Yilgarn Craton also have significant paleovalley-hosted uranium potential. In these regions, uranium-rich

Proterozoic crystalline basement provides potential source rocks (e.g., Hiltaba Suite granites) (Fig. 2) (Hou et al., 2007b).

In northern China, pre-Jurassic rocks, particularly the Archean and Paleoproterozoic basement, contain relatively high concentration of uranium; these represent a significant uranium source for Mesozoic paleovalley-related uranium deposits (Li et al., 2008). The source rocks of the northeastern Ordos Basin sediments, for instance, are rich in uranium; strata of middle Variscan – early Yanshan ages typically contain an average of 4 ppm uranium and Indosinian granites contain 12 ppm uranium (Li et al., 2008). These have contributed significant quantities of uranium for paleovalley-hosted uranium deposits in the Ordos Basin (Li et al., 2008).

Sandstone-hosted (roll-front) deposits

Sandstone uranium deposits contain diagenetic and/or epigenetic concentrations of uranium minerals, generally uraninite (UO_2) or coffinite ($USiO_4$) and are typically hosted by fine to coarse-grained sands deposited in fluvial, alluvial, lacustrine or marginal marine environments. The majority of deposits (e.g., in USA, Kazakhstan, Australia, Niger, Uzbekistan, Gabon, and South Africa; Finch and Davis, 1985; McKay and Mieziotis, 2001) occur in essentially undisturbed continental sandstones of Mesozoic and Cenozoic age (Fig. 3). Deposits in older host rocks are known but are less common (e.g., Paleozoic sandstone-hosted uranium roll-fronts in Western Australia and Europe (IAEA, 2009). Mineralisation associated with

Age			SANDSTONE		LIGNITE		CALCRETE	
Ma			Australia	China	Australia	China	Australia	China
Cenozoic	Quaternary	Holocene						
		Pleistocene						
	Neogene	Pliocene	U • Eucla Basin				U • Yeelirrie deposit • Lake Way deposit • Maitland deposit • and others in W.A.	
		Miocene	U • Lake Eyre Basin • Eucla Basin					?
	Paleogene	Oligocene	• Lake Eyre Basin • east Eucla Basin • Pirie Basin • west Eucla Basin					
		Eocene	U		U • Eucla Basin			
Mesozoic	Cretaceous	Late						
		Early	U • Carnarvon Basin • Eromanga Basin	U • Songliao Basin		?		
	Jurassic			U • Ordos Basin		U • Tianshan Foldbelt		
	Triassic							
Paleozoic	Permian							
	Carboniferous		U • Ngalia Basin • Amadeus Basin • Canning Basin					
	Devonian							
	Silurian							
	Ordovician							
	Cambrian							

Figure 3. Distribution of sandstone, lignite and calcrete-hosted uranium deposits in Australia and China through geological time (for the deposits located in the basins/regions see Figure 1), and age-ranges (grey vertical bars) of the three types of paleovalley-related deposits worldwide. Note: for these three deposit types the ages shown are those of the host rocks.

redox fronts near the contact of reduced and variably oxidised sands can be clearly demonstrated in several deposits in Australia and China (e.g., Curtis et al., 1990; Li et al., 2008). In Australia, sandstone uranium deposits are known from three states, Northern Territory, Western Australia and most notably South Australia. The uranium fields and basins containing these deposits are the Lake Eyre Basin, Eucla Basin, Westmoreland, Pandanus Creek field, Amadeus Basin, Ngalia Basin, Gunbarrel Basin, Carnarvon Basin and Canning Basin (Fig. 1; McKay and Mieztis, 2001). Recently, potential in other areas has been identified through greenfield discoveries, as with the Pirie Sub-basin of South Australia (e.g., Blackbush deposit) and Cenozoic paleovalleys of Western Australia (e.g., Theseus deposit). The significant sandstone uranium deposits in China are mostly located in northern China, including the Ordos and Songliao Basins (Fig. 1b).

Within sandstone deposits, impermeable shale/mudstone (sometimes lignite or coal) units are interbedded in the sedimentary sequence and often occur immediately above and below the mineralised sandstone. Uranium is precipitated under reducing conditions caused by various reducing agents within the sandstone including: carbonaceous material (e.g., detrital plant debris and marine algae), sulphides (pyrite, H_2S), petroleum (including gas), and

interbedded mafic volcanics with abundant ferro-magnesian minerals (e.g., chlorite).

A general model widely used to guide exploration is that uranium is liberated from a source rock area and is mobilised and circulated in oxidised fluids/ground waters through porous strata until it encounters a reducing environment where it is precipitated; i.e., uranium mineralisation results from the interaction of uranium-rich oxidising fluids and reduced lithologies (at redox fronts) (Fig. 4) (e.g., Adams and Smith, 1981; Dahlkamp, 1993; De Voto, 1978a; Fischer, 1970; Goldhaber et al., 1983; Grutt, 1971; Nash et al., 1981). This conventional model has proved robust and a useful predictive tool leading to the discovery of many sedimentary uranium deposits across the world, including Australia and China. The uranium source and type and abundance of reductant in the ore-bearing sedimentary sequence are of critical importance for the formation of sandstone uranium deposits. Sediments in close proximity to the redox boundary typically show yellow to orange colouration resulting from iron oxyhydroxide staining on the oxidised side of the redox boundary, changing progressively towards darker tones within reduced sediments. These alteration zones around ore are associated with elevated radioactivity. Therefore, the main controlling factors on the location of uranium ore are the interplay of uranium source,

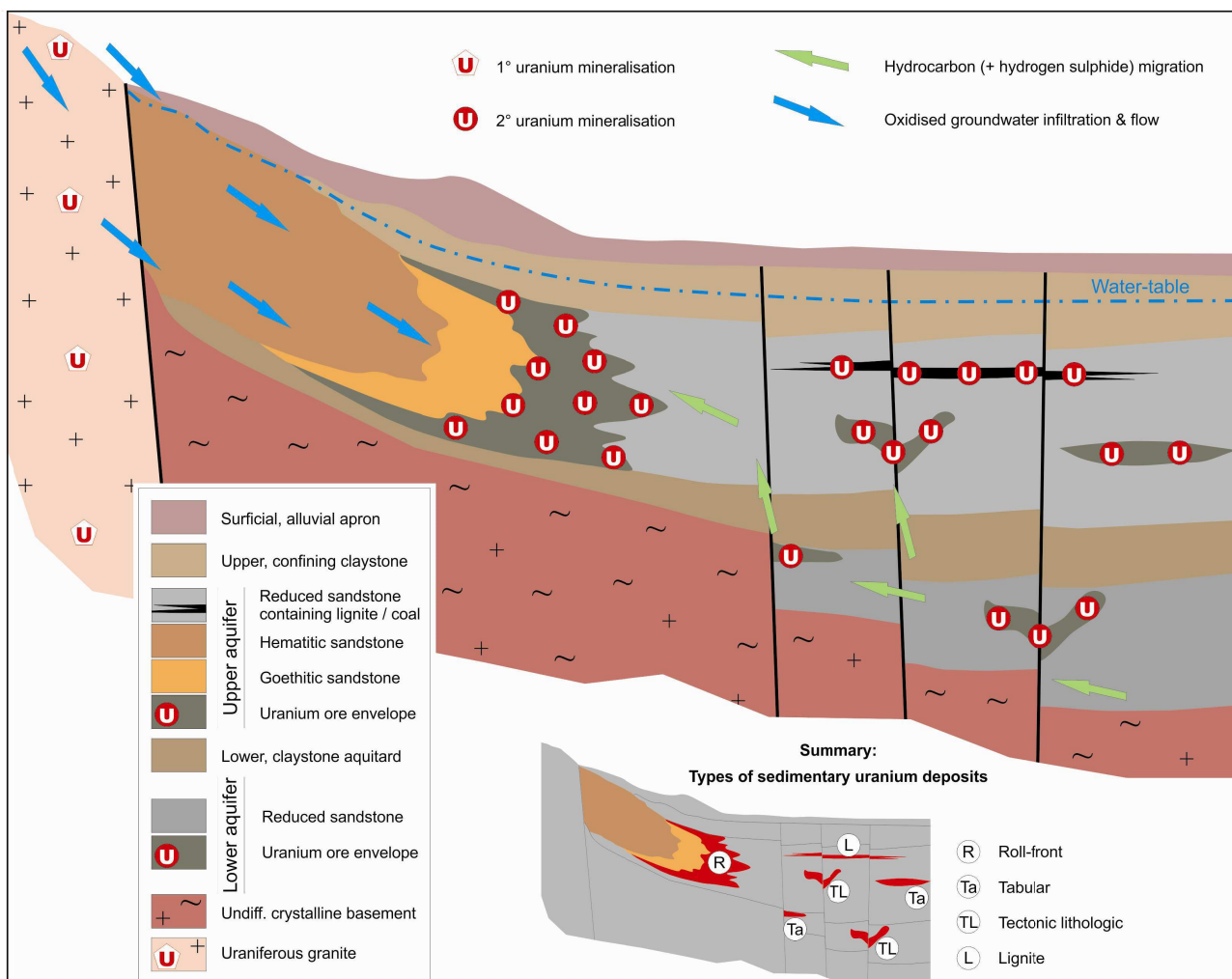


Figure 4. Palinspastic cross-section model for sedimentary uranium deposits, highlighting the role of aquifer flow (e.g., Devoto, 1978a) and REDOX state, formation of roll-front mineralisation and the stratigraphic relationship of tabular, tectonic lithological and lignite uranium mineralisation.

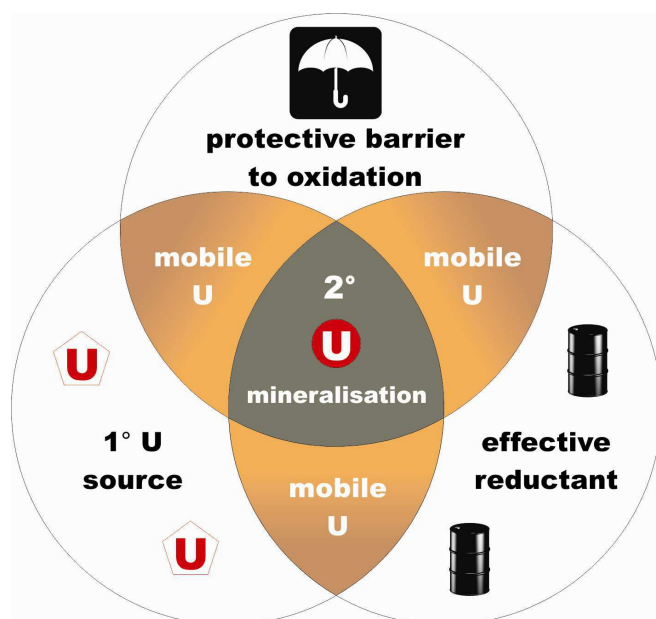


Figure 5. Schematic illustration of the junction of three independent parameters required to form an economic sandstone-hosted uranium deposit.

sedimentary facies, uranium-bearing fluids/groundwater, and the proportion of reducing agents (viz carbonaceous matter, sulfides, hydrocarbons and interbedded ferro-magnesian-rich mafic volcanic; e.g., Spirakis, 1996). Uranium mineralisation accumulates at sites that are protected from oxidising groundwater influx (Fig. 5).

Based on the shape of the orebody and its relationship to the depositional or structural environment, sandstone uranium deposits can be subdivided into four types (these may be gradational into each) (e.g., Fischer, 1970; De Voto, 1978b; Nash et al., 1981; Dahlkamp, 1993; IAEA, 2009). In terms of potential size of contained resources, first are roll-front deposits, arcuate bodies of mineralisation that cross-cut sandstone bedding as described from the Honeymoon deposits, South Australia and the Dongsheng deposits, northern China (McKay and Miezitis, 2001; Li et al., 2008). Second are tabular deposits. These are irregular, elongate and lenticular bodies parallel to the depositional trend, that commonly occur in paleovalleys that incise basement rocks. Examples include the Honeymoon deposits, South Australia. Beverley deposit in South Australia is another example of a likely tabular deposit hosted within a paleochannel that has incised sediment of similar age. Third are basal channel deposits, including uranium mineralisation distributed in paleovalleys that incise underlying crystalline basement or sedimentary bedrocks (e.g., Honeymoon and Blackbush of South Australia and examples from China, Canada and Russia) (Boyle, 1982; Bush, 2000; IAEA, 2009; Li et al., 2008). Fourth are tectonic lithologic deposits (these occur in sandstones adjacent to a permeable fault zone, distributed along permeable fault zones cutting sedimentary sequences; e.g., Dongsheng deposits, northern China) (Li et al., 2008) (Fig. 4). These deposits are characterized by strong structural control of mineralisation distributed along high-angle tectonic faults cutting the host sedimentary sequences (Dahlkamp, 1993; IAEA, 2009). Tabular, basal channel and roll-front mineralised bodies form along the contact between sand and clay horizons and at paleochannel bases and margins, while tectonic/lithologic deposits may occur in sandstones adjacent to a permeable fault zone.

Uranium-bearing mineral detritus and rock fragments derived from weathered bedrock are incorporated and deposited with the channel sediments. The uranium is leached under oxidising and slightly acidic conditions and is mobilised in groundwater moving through the sediments, with precipitation of mineralisation commonly accompanying diagenesis of the sediments to form tabular bodies. By way of contrast, in roll-front deposits, uranium is introduced into the host rocks by oxidising waters after diagenesis (Finch and Davis, 1985). Roll-front deposits form in a dynamic fluid regime by gravity-driven groundwater moving in the down-dip direction along permeable strata (Fig. 4). The gravity gradient that controls continuous flux of groundwater is considered to be related to successive uplift of the basement rocks exposed at the basin margins (Dahlkamp, 1993). Such is the case for strata of the Frome Embayment and Callabonna Sub-basin that overlie faulted crystalline basement rocks of the Curnamona Province in South Australia (Figs. 6 and 7). Due to diagenetic and epigenetic modifications, the idealised structure of uranium mineralisation concentrated along a distinct boundary at or near the contact with obvious reduced materials, as shown in Figure 4, may not always be present, such as Beverley deposits of South Australia. The features controlling uranium deposition can be made complex, or completely destroyed, by multiple groundwater and/or hydro-thermal pulses, in particular, when uranium mineralisation is modified and remobilised by post-ore, reduced/oxidised and saline solutions (Abzalov, 2012).

A diversity of sandstone-hosted deposits across Australia

Many of Australia's sandstone-hosted uranium deposits occur in paleovalleys and related terraces developed in and adjacent to sedimentary basins of Carboniferous, Cretaceous and Cenozoic age (Figs. 1 and 3). In South Australia paleovalley-related, channel sandstone uranium deposits include Beverley, Honeymoon, East Kalkaroo, Goulds Dam, and Blackbush. Other major uranium deposits are hosted in terrestrial (fluvial) sediments flanking bedrock highs where paleochannel control is less apparent, e.g. Four Mile East, Pepegooona and Pannikin. Deposits at Beverley, Pepegooona, Pannikin, Four Mile and Honeymoon have been, or are presently mined by *in situ* leach (ISL) mining methods.

Other deposits are Manyingee, Carley Bore, Oobagooma, Theseus, Ponton, and Mulga Rock in Western Australia, Bigrlyl, Walbiri, Afghan Swan, Angela and Pamela in the Northern Territory (Fig. 1). Bigrlyl and Walbiri deposits occur along the margin of the Ngalia Basin where the host rocks were deposited in a braided-fluvial system of late Devonian-Carboniferous age (Fig. 3; e.g., Fidler et al., 1990). To the north, Angela and Pamela deposits are developed in the Amadeus Basin, within a similar stratigraphic setting to the Ngalia Basin (Figs. 1 and 3) (Borshoff and Faris, 1990). In the Canning Basin, the Oobagooma uranium deposit is hosted by the Yampi Sandstone (Early Carboniferous) within a fault-bound paleodrainage system, with high-grade uranium mineralised zones formed in classic roll-fronts and associated with abundant organic matter and pyrite (McKay and Miezitis, 2001; Brunt, 1990).

Several roll-front sandstone-hosted uranium deposits in Western Australia, such as Manyingee and Carley Bore, occur along the eastern margin of the Carnarvon Basin (Figure 1), preserved in a paleovalley of Cretaceous age between basement highs (Penney, 2012). Theseus deposit, discovered in 2009 in Western Australia close to the border

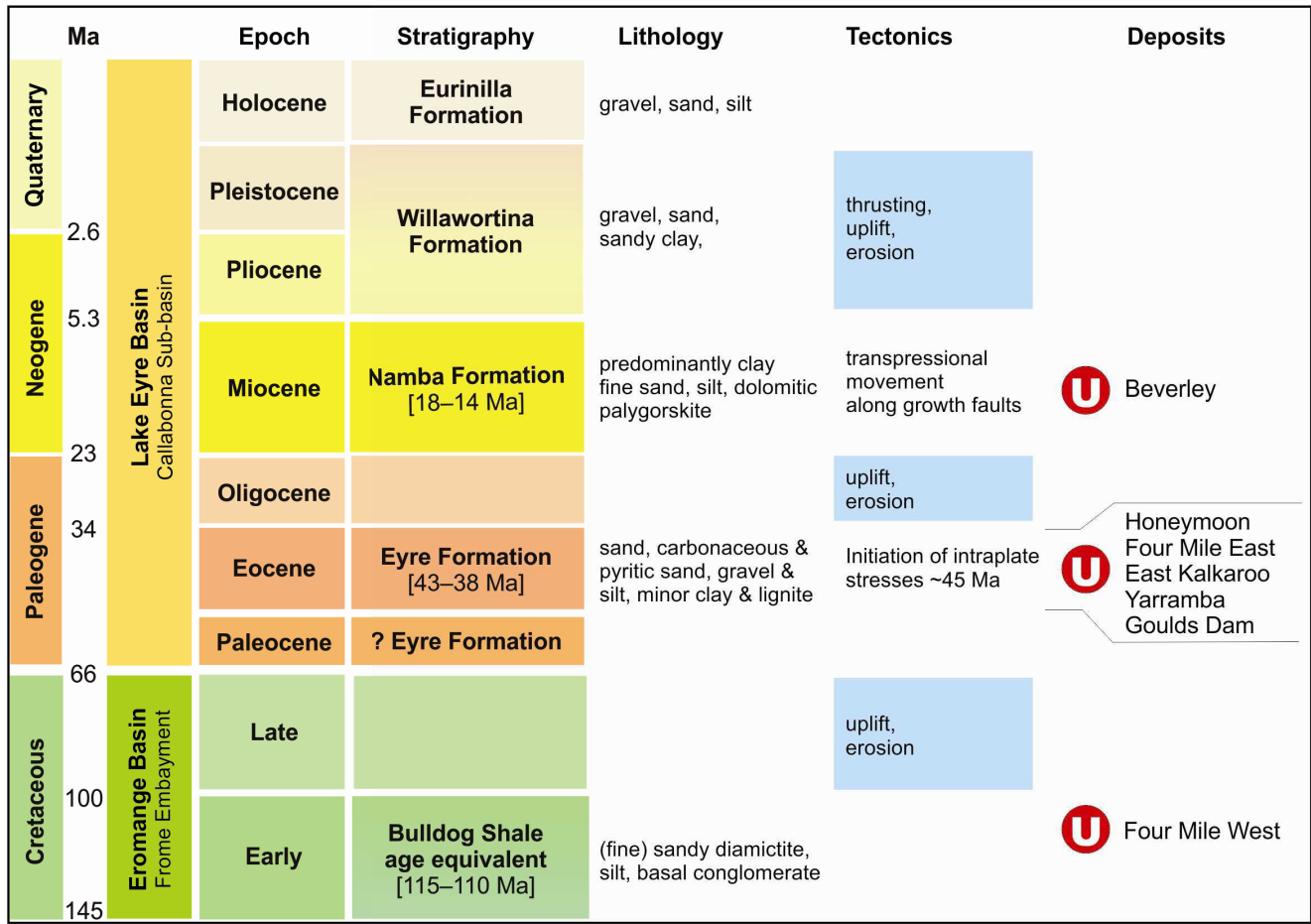


Figure 6. Stratigraphic position of the sandstone-hosted uranium deposits in the Frome Embayment and Callabonna Sub-basin, South Australian.

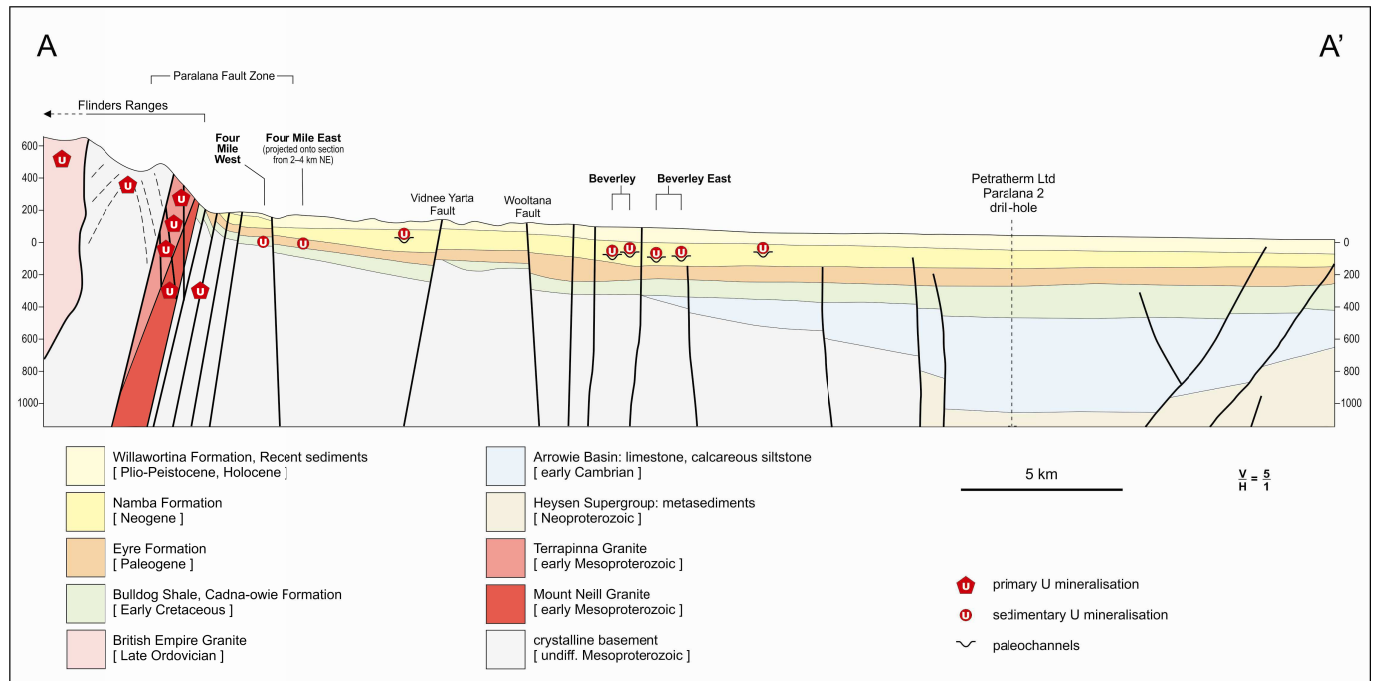


Figure 7. Idealised geological cross-section (A-A' inset, for the location see Figure 2b) across the eastern margin of the northern Flinders Ranges, Four Mile West and Beverley uranium deposits, and the northern Poontana Trough. Vertical scale is exaggerated five-fold. Modified from Hou et al (2012).

of the Northern Territory, comprises roll-front uranium mineralisation hosted within an Eocene paleovalley that drained the region between the Ngalia Basin and crystalline basement of the Arunta Province (Penney, 2012). Another recent (2010) discovery of paleovalley-related uranium, Afghan Swan prospect in the Northern Territory, is in lower Cenozoic sands deposited near the base of paleovalleys developed in the central area of the Ngalia Basin (Fig. 1) (Thundelarra Exploration Ltd, 2012). At Mulga Rock deposit (Western Australia) on the western Eucla margin, uranium mineralisation is within oily, lignitic layers interbedded with sand and clay, within buried paleovalleys.

In contrast to the deposits listed above, uranium in the world-class, Four Mile West deposit is hosted within a marine glacial sediment composed of “rain-out” sandy diamictite and is unrelated to Mesozoic paleovalley architecture. Four Mile West is the only sandstone-hosted uranium deposit in the Paralana area that is hosted entirely within Eromanga Basin marine sediments. The host sandy facies is equivalent in age to the Bulldog Shale (late Early Cretaceous), (Michaelsen et al. 2012) deposited during marine onlap of the crystalline basement of the Mount Painter Inlier (Fig. 7). The diamictite reflects conditions of Early Cretaceous glaciation previously recognised in the region from lodgement till deposits in the overlying Cadna-owie Formation (Alley and Frakes, 2003).

Callabonna Sub-basin of the Lake Eyre Basin, South Australia

Notwithstanding the newly discovered uranium deposits and prospects within Western Australia and the Northern Territory, Australia’s premier sandstone-hosted uranium province comprises the south-eastern portion of the Callabonna Sub-basin, the eastern part of the larger Lake Eyre Basin (Cenozoic) that comprises thick (in places > 400 m) episodic fluvial, alluvial and lacustrine sediments (Callen et al., 1995; Fig. 2). The Callabonna Sub-basin contains the paleovalley-related Beverley, Honeymoon, Oban, and Goulds Dam uranium deposits; other non-paleovalley-related deposits form the Paralana uranium field (Michaelsen et al., 2012: viz Four Mile East, Pepegooona, Pannikin), (Fig. 2). To the west of the Birdsville Track Ridge, the Tirari Sub-basin also has potential to host sedimentary uranium within paleovalleys (Fig. 2; Hou et al., 2006).

The basal unit of the Lake Eyre Basin is the Eyre Formation (latest Paleocene to mid-Eocene), which is comprised of mainly coarse-grained lithologies including fluvial sandstone, carbonaceous clastics and conglomerate. Fluvial channels of paleovalleys, headwatered in the eroded, weathered basement rocks of the Olary region, incised Cretaceous and older rocks across the southern half of the Callabonna Sub-basin (Conor, 2004), and coalesced to form amalgamated blanket-sands toward the centre of the basin (Callen, 1990). Uranium-enriched source rocks of the northern Flinders Ranges and Olary region, including numerous small uranium vein and breccia-hosted deposits within crystalline rocks of the Mount Painter Inlier (Fig. 7) provided an abundant source of uranium to Cenozoic sediments of the Callabonna Sub-basin.

Overlying the Eyre Formation, early Miocene to Pliocene clays, sands and carbonates of the Etadunna and Namba Formations were deposited in extensive lakes and associated fluvial and shoreline environments, that were blanketed subsequently by Pliocene to Quaternary fluvial, aeolian and playa-lake sediments, in response to drier climatic conditions across the interior of the Australian continent.

Honeymoon

Honeymoon deposit, discovered in 1972, became Australia’s fourth operating uranium mine in 2011. It is a typical roll-front uranium deposit, located in the Yarramba paleovalley of the Callabonna Sub-basin. Uranium mineralisation is hosted by sub-horizontal permeable sands of the Eocene Eyre Formation (Figs. 2 and 6). Here, Eyre Formation consists of immature, pyritic, carbonaceous sands and gravels interbedded with lignite and kaolinite-illite-montmorillonite clays, and the sands are overlain by impermeable Miocene clays of the Namba Formation. The Yarramba paleovalley drained and incised weathered basement rocks of the southern Curnamona Province and was infilled by up to 50 m of (now uranium-bearing) Eyre Formation, occurring as three sand members, the ‘basal sand’, ‘middle’ and ‘upper sands’, which are separated by clay layers (Reif, 2000). Uranium mineralisation, primarily as coffinite, occurs in five distinct horizons separated by thin clay seams and was sourced from nearby uraniferous granite (Honeymoon-type granites) (Fricke, 2008; Fricke and Reid, 2009). The Honeymoon deposit was formed at an extensive reduction-oxidation boundary at the paleovalley margins (Reif, 2000; Hou et al., 2007b).

Beverley

At **Beverley** deposit (discovered in 1969), uranium mineralisation assumes tabular and lenticular bodies, comprising mainly coffinite that coats quartz grains and fills void space. The mineralisation is hosted by sandy infill within a broadly north-south striking paleovalley system, immediately east of Poontana Fault zone. The host unit to Beverley mineralisation is a sandy paleochannel incised within the uppermost Namba Formation (Miocene). Regionally, the Namba Formation is mainly clay and silt, intercalated with lesser quantities of fine channel sand with subordinate carbonate and sapropelic coal near the base (Michaelsen and Fabris, 2011). Development of the Beverley paleochannel was controlled by syn-sedimentary activity on the Poontana Fault system (Fig. 7). In addition to coffinite, there is subordinate uraninite (as nodules) and very minor carnotite (Wülser et al., 2011). U-mineralised nodules nucleated around Co-rich pyrite with S isotope compositions ($\delta^{34}\text{S} = 1.0 \pm 0.3\text{‰}$) suggestive of early diagenetic lacustrine origin (Wülser et al., 2011). U-Pb dating of coffinite and carnotite indicates that uranium mineralisation formed predominantly during Pliocene time (6.7–3.4 Ma; Wülser et al., 2011), corresponding to an episode of uplift and erosion of the northern Flinders Ranges and deposition of alluvial fans comprising the Willawortina Formation, which overlies the Namba Formation.

Clastic sediments that comprise the middle and upper Namba Formation are very low in organic matter (Michaelsen and Fabris, 2011). Indeed, the concentration of *in situ* (detrital) organic matter within the Namba Formation is considered too low to account for the quantity of economic uranium mineralisation at Beverley. Hydrocarbon gas, derived from the maturation of organic matter within the Poontana Trough (Fig. 7) is the most plausible uranium reductant that can be implicated in the formation of the Beverley uranium deposit.

Paralana uranium field

Deposits of the Paralana uranium field (Michaelsen et al., 2012) are not paleovalley deposits *sensu stricto*. However, individual deposits (viz Four Mile West, Four Mile East, Pannikin and Pepegooona

are considered here, because subsurface fluid-flow in the Paralana Embayment (Michaelsen et al., 2012) is focussed in a manner similar to that within a buried paleovalley. Common to each deposit is that it is hosted within unlithified sand. However, as indicated previously, Four Mile West deposit is hosted within a glacial marine unit of Early Cretaceous age. By contrast the nearby Four Mile East deposit (Fig. 7), and the Pannikin and Pepegooona deposits, within the Paralana Embayment are predominantly hosted within alluvial fans and amalgamated fluvial sands of Eocene age (Eyre Formation).

Mineralisation at Four Mile West is dominantly uraninite, along with various REE and U-bearing phosphate minerals and associated pyrite and kaolinite. Four Mile East and Four Mile West are distinct deposits, discovered in 2005. The Four Mile deposits are on the margin of the Frome Embayment and proximal to primary uranium mineralisation in crystalline basement rocks of the Mount Painter Inlier (Figs. 1, 2 and 7). The ore zones are situated between the Paralana Fault Zone, which defines the eastern edge of the northern Flinders Ranges, and the Poontana and Wooltana faults, where basement has been uplifted in a horst structure forming a barrier to easterly groundwater flow in the Cretaceous and Eocene sediments (Fig. 7). The combined indicated and inferred resource at Four Mile West and Four Mile East deposits is 9.8 million tonnes at 0.33% U_3O_8 , containing 32 000 tonnes U_3O_8 which make this the largest and highest grade sandstone-hosted uranium field in Australia (Penney, 2012; Johnston, 2013).

The Pepegooona Deposit, discovered in 2009, is located 10 km to the north of Beverley Uranium Mine. Uranium-bearing sands of the Eyre Formation are within 200 m of outcropping Mesoproterozoic granites of the Mount Painter Inlier. The mineralisation is developed within complex redox fronts. The ore zone is overlain by a thin groundwater silcrete, and this in turn, is overlain by Namba Formation silts and Willawortina Formation gravels. The host sands are underlain by Cretaceous silts of the Bulldog Shale (Fig. 6) (McConachy, 2009). Further to the north, drill intersections of uranium in several sand horizons within the Namba Formation at Yagdlin prospect, approximately 12 km north of Beverley, have been reported (Giralia Resources, 2007). These possibly represent the northern-most extent of the Paralana uranium field.

Other significant uranium deposits and prospects in the Callabonna Sub-basin are hosted in paleovalley fluvial channel sands of the Eocene Eyre Formation. These include Oban deposit (discovered in the 1980s; located in the Lake Charles paleo-valley; Curnamona Energy, 2009; Tonkin, 2009), the East Kalkaroo deposit (discovered in 1971, located in the Yarramba paleovalley, 2.5 km east of Honeymoon; Uranium One, 2007), the Goulds Dam deposit and the Billeroo prospect (discovered in 1974, located in the Billeroo paleochannel near the confluence with the Curnamona paleovalley; Curtis et al., 1990; Reif, 2000), the Yarramba prospect (discovered in 1970, located in the Yarramba paleovalley, 12 km north of the Honeymoon deposit) and Junction Dam prospect (discovered in 2009, 18 km east of Honeymoon deposit; Wilson, 2012). Significant uranium anomalies have been reported from other paleovalleys, including the Curnamona paleovalley, Erudina paleovalley, Wyambana paleovalley, and Stickhole paleovalley (Fabris et al., 2004).

Eucla Basin

The Eucla Basin and its peripheral paleovalleys, stretching from the eastern Yilgarn Craton of Western Australia to western Gawler

Craton of South Australia, host numerous uranium prospects (Fig. 1). Major paleovalley systems with extensive tributary networks have been identified in the onshore paleodrainage catchment of the Eucla Basin (Fig. 2) (e.g., Benbow et al., 1995; Alley et al., 1999; Clarke 1993; Hou et al., 2003; 2007a; 2011). Known uranium occurrences are presently confined to the western and eastern margins of the Eucla Basin where crystalline basement rocks are potential source areas for uranium (Figs. 1 and 2). Exploration for paleovalley-hosted uranium commenced in the mid 1970s, initially focusing on the eastern Eucla paleodrainage, specifically the Kingoonya and Narlaby paleovalleys. This resulted in discovery of the Warrior prospect (discovered in the 1970s in Warrior paleochannel), and Ealbara prospect (discovered in the early 1980s), both situated in tributaries of the Kingoonya paleovalley (Curtis et al., 1990), and four Yarranna prospects (up to 3550 ppm U_3O_8) in the Narlaby paleovalley and Yaninee prospect in the Yaninee paleovalley (Binks and Hooper, 1984). Uranium present in the eastern Eucla paleovalleys may have been sourced from Hiltaba Suite granites that are widespread on the Gawler Craton, variably weathered, and typically contain uranium contents 2-3 times background levels. The eastern Eucla paleo-drainage actively incised weathered basement during early to middle Eocene times with flow rates decreasing over time such that sandy valley fill and lignitic clays gave way, during Miocene time, to largely chemical carbonate sedimentation in a series of discontinuous lakes strung out along the major drainage lines (Fig. 2) (e.g., Hou et al., 2007b). Anomalous levels of uranium have been reported also in other paleodrainage networks, including the Woldra paleovalley and Lake Bring estuary (16 to 643 ppm U_3O_8) (Curtis et al., 1990) and the Thurlga paleovalley (8 m at 106 ppm U_3O_8) (Adelaide Resources, 2009).

Paleovalleys along the western margin of the Eucla Basin drain potential uranium source rocks of the Yilgarn province. Uranium discoveries within this drainage network include the Mulga Rock and Ponton uranium deposits where extensive drilling has been undertaken in recent years (Penney, 2012). These uranium deposits lie within the Raeside paleovalley system, which incised deeply weathered crystalline rocks of the Yilgarn Craton and Albany-Fraser province and can be traced for more than 100 km across the western Eucla margin and eastern Yilgarn Craton. The Mulga Rock uranium deposits are characterised by numerous mineralised zones within interbedded sand and lignite (see 'Lignite deposits' below) (Fig. 14), which are hosted by middle Eocene sediments within a sequence of up to 100 m of Paleogene fluvial, estuarine and lacustrine sediments. These overlie preserved remnants of Cretaceous and Permian sediments (Macfarlane and Inwood, 2010). Drilling at Mulga Rock has outlined four separate deposits, Ambassador, Shogun, Emperor and Princess. The Ponton deposits, containing eight prospects are hosted in the same paleodrainage network as Mulga Rock (~25 km to the south) (Fig. 1).

Pirie Sub-basin

Recent exploration in the Cenozoic paleovalleys of the Pirie Basin resulted in the greenfield discovery of Blackbush and Plumbush deposits (Mullaquana project) in 2007 (Fig. 2). The uranium mineralisation (coffinite and uraninite) at Blackbush (inferred resource of 63 million tonnes at 0.029% eU_3O_8 containing 18 300 tonnes U_3O_8 , at cut-off grade of 0.01% eU_3O_8) (Bluck, 2009a, b, Uranium SA, 2013) is hosted within a Cenozoic sand unit, at and below the contact between carbonaceous to lignitic mature, monomictic sand units of

Eocene age (Kanaka Beds) and an overlying oxidised, mature, polymictic sand unit of Miocene age. The uranium-bearing paleovalleys include channels that incise bedrock of weathered Hiltaba suite granite that is locally enriched in uranium and recognised throughout the region as a potential uraniferous source rock (Fig. 8). The thicker and higher grade zones in the sediments appear to trace the deeper parts of the paleovalleys (up to 26.5 m at 0.19% eU₃O₈). Uranium mineralisation has been located also at additional prospects Sugarbush and Emubush which combined with Blackbush and Plumbush make up the Samphire uranium project. These recent discoveries of paleovalley-hosted uranium within the eastern Gawler Craton region of South Australia significantly upgrade the exploration potential of this region for further discoveries of paleovalley-hosted uranium mineralisation.

Cases from China

The Ordos and Songliao Basins of northern China contain significant paleovalley-hosted sandstone uranium deposits (Figs. 9-12). These Mesozoic basins are also well-known for producing oil and gas (e.g., northeastern Songliao Basin) and coal (Ordos Basin).

Discovery of the sandstone uranium deposits in the early 2000s ensured the Ordos Basin became a more important energy resource region, in addition to the oil-gas and coal resources (Li et al., 2008). Uranium mineralisation occurs in the reduced (grey-green and grey) sandstones of the middle Triassic Zhiluo Formation, which were deposited in Jurassic braided channels (Fig. 9) (Li et al., 2005, 2007). Uranium is concentrated in the transitional zones between gray-green and grey sandstones of the Zhilou Formation of Middle Jurassic age (Li et al., 2005), in similar manner to those of the Monument Valley and White Canyon districts, USA, which were deposited in late Triassic braided and meandering channels (Dahlkamp 1993). As in the Beverley deposit of South Australia, the interface of oxidised and reduced phases is not obvious in the uranium deposits of the Ordos Basin. The greenish colour is thought to result from secondary oil-gas reduction process, and is due to acicular-flakey chlorite coating the surfaces of sand grains (Li et al., 2008). Extrinsic reductants emanating from deeper oil and gas reservoirs have been proposed also as a source of reductants for giant sandstone-hosted uranium deposits in Kazakhstan (Jaireth et al., 2008). The critical components needed to precipitate and concentrate uranium require multiple sources including the surrounding Archean-Early Proterozoic basement and Mesozoic uranium-bearing strata, and oil-gas fluids. These came together to form uranium deposits during several recognised mineralising processes and in stages, recognised as tectonic 'dynamic-static' coupling movements, superposition of paleo-phreatic oxidation and interlayer oxidised mineralisation, and composite transformation of oil-gas and thermal fluids, as shown in Figure 10 (Li et al., 2008).

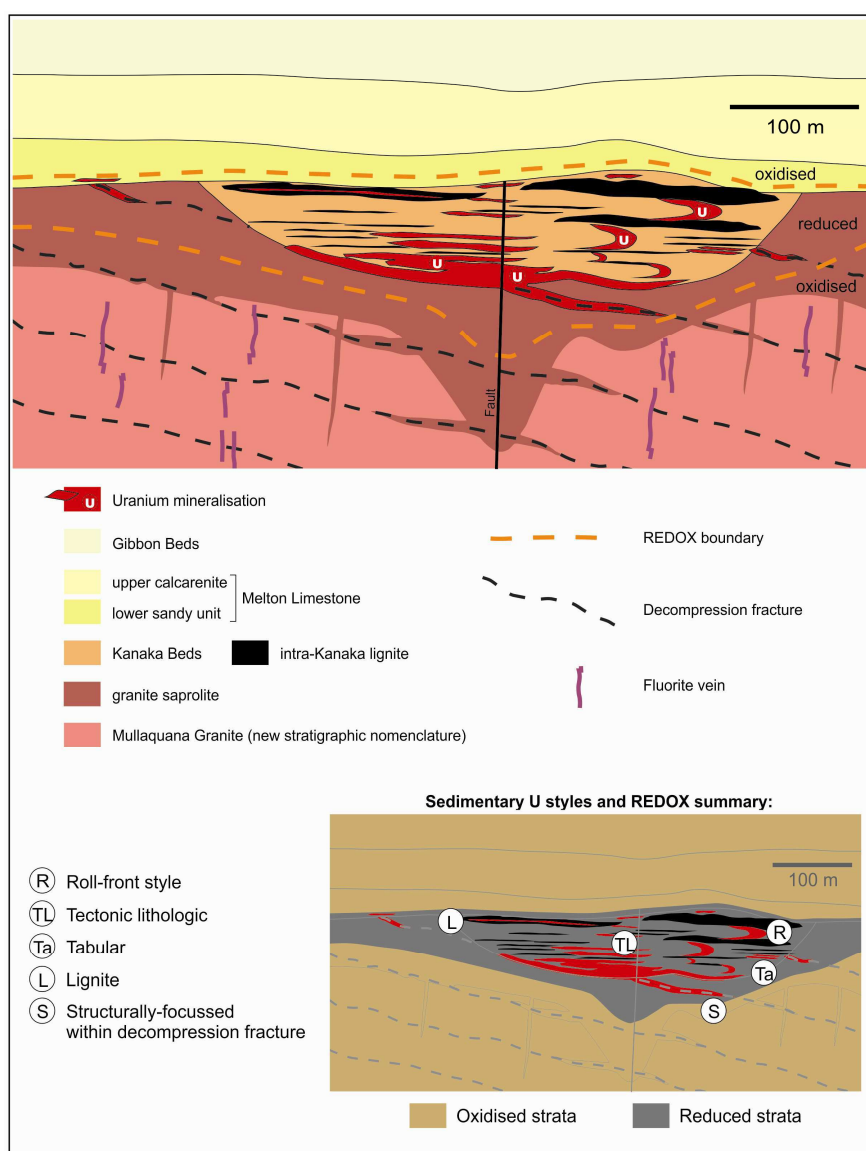


Figure 8. Geological cross-section through Blackbush uranium deposit (Mullaquana project), Pirrie Sub-basin, South Australia.

The Qian Jia Dian (QJD) uranium deposit is located in the QJD fault-controlled sub-basin within the Songliao Basin; it is hosted in channel sediments of the late Cretaceous Yaojia Formation (K2) (Fig. 11). The Yaojia Formation mainly consists of sandstone, siltstone and mudstone. These rocks are vertically graded to form a typical braided fluvial facies. The formation of uranium deposits resulted from four stages: 1) initial enrichment of uranium during deposition of Yaojia Formation braided channel sediments; 2) tectonic uplift and infiltration of U-bearing oxidised water; 3) effusion of oil-gas and brine through faults and 4) alteration of sand bodies under conditions of good permeability and abundant reduced matter (Fig. 12) (Li et al., 2008).

Surficial (Calcrete) deposits

Paleovalleys containing calcrete are important hosts for uranium mineralisation in Western Australia and southern Africa, particularly Namibia (IAEA, 2009). Surficial uranium deposits are broadly defined as young (Cenozoic, Fig. 3), near-surface uranium concentrations

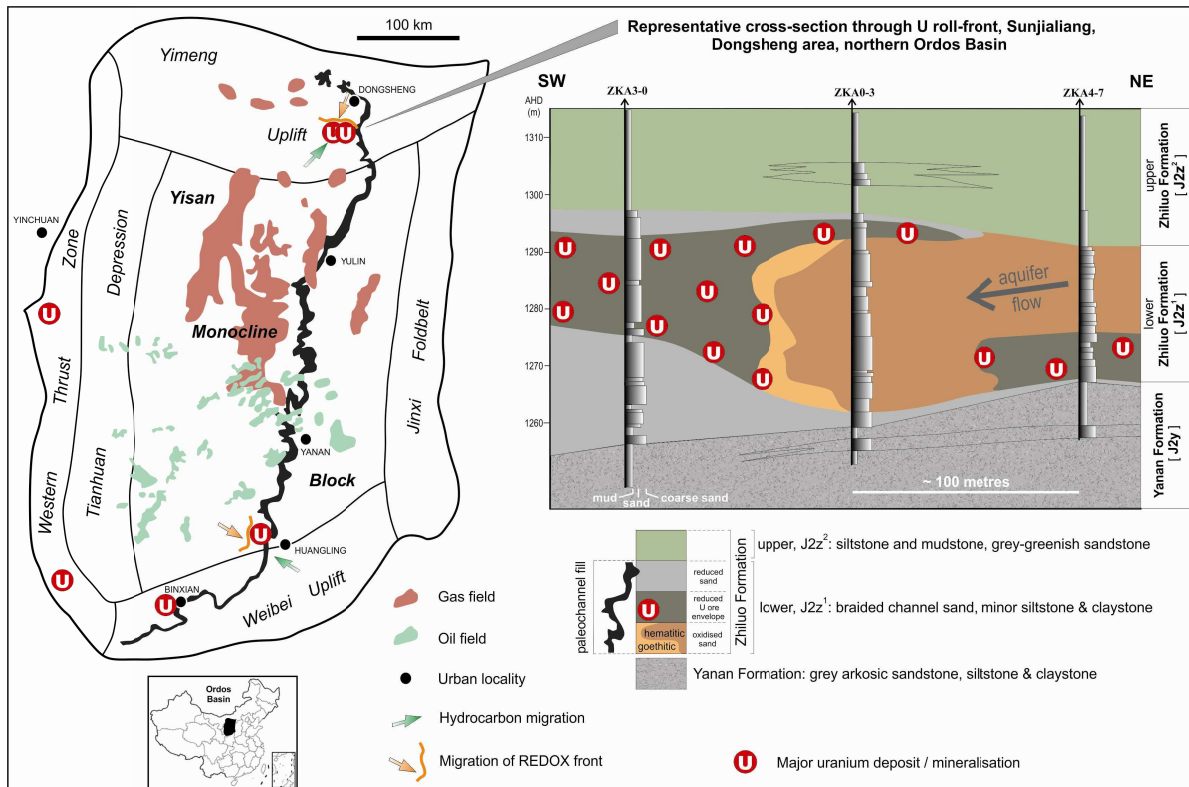


Figure 9. Major paleovalley-related uranium deposits of Ordos Basin, northern China. Representative cross-section through uranium roll-front, Sunjialiang, Dongsheng area, northern Ordos Basin. Rollfront uranium enriched in braided paleochannels.

overlie and are adjacent to weathered Archean granite and greenstone basement rocks, which provide a source of soluble uranium and vanadium necessary to form carnotite (Mann and Deutscher, 1978). The calcrete formed in the paleovalley sediments is relatively young, post Pleistocene (Mann and Horowitz, 1979) and reflects the change to more arid conditions. Carbonate was precipitated from groundwater usually in the central and lower regions of the paleovalley where the watertable was close to the surface and evaporation and evapotranspiration rates were sufficiently high to concentrate calcium and magnesium ions. According to Mann and Horowitz (1979), carbonate deposits formed initially within the zone of saturated sediments. Continued deposition and crystallisation of carbonate caused mounding of older carbonate, which displaced overlying sediments and was pushed upwards above the watertable where the carbonate was recrystallised and hardened. Uranium in groundwater, as uranyl carbonate complexes, combined with vanadium and potassium to precipitate carnotite in areas of valley calcretes either through groundwater mixing or changed chemical conditions resulting in the solubility product of carnotite being exceeded (Gaskin et al., 1981).

A typical model for the origin and formation of surficial calcrete-hosted uranium deposits is summarised in Figure 13 based on common key features identified in Australian deposits (e.g., Yeelirrie and Lake Way). The uranium sourced from uraniferous granites in the region is transported in mildly oxidizing saline alkaline groundwater solutions in constricted drainages to semi-closed basins with variable evaporative conditions. General characteristic of calcrete-hosted deposits, with reference to Howell et al (2009) and McGeough, pers comm. (Toro Energy Ltd., 2009) include:

- significant areas of uranium enriched bedrock, which are obvious in airborne radiometric imagery at both regional and continental

scales, generally derived from Archean and Proterozoic weathered granites;

- mostly Cenozoic palaeovalley systems drained these uranium enriched bedrock areas and discharged into lakes, as well as hosting channel calcrete formations;
- a periodic wet and dry climatic region whereby there were long periods of wet developing drainage systems and dry allowing evaporation (e.g., Wiluna of WA and Napperby of NT);
- carnotite mineralisation in calcrete usually increases in the 'deltaic' segments of fluvial discharge into broader lake systems adjacent to paleovalleys;
- almost all deposits show remarkably similar lithologies, i.e., deeply weathered zone of saprolitic clay overlying a granite basement, and/or alluvial clay overlying highly weathered basement with anomalous vanadium content;
- uranium host materials formed in low-energy conditions dominated by calcrete and silcrete (e.g., approximately 25% of the carnotite mineralisation of the Wiluna and Napperby deposits of Australia is hosted in calcrete/silcrete layers), fine sand/silt and clay (e.g., approximately 70% of the carnotite mineralisation in these Australian deposits is hosted in silt and clay);
- the carnotite mineralisation is associated with secondary deposition of calcite, dolomite, gypsum, salt, celestine and barite indicative of evaporative brine concentration;
- as a common feature, the calcrete uranium mineralisation is associated with highly saline water (1-3 times sea water salinity), even though the salinity of both upstream and downstream groundwaters is significantly lower;
- carnotite mineralisation occurs in fractures and vughs within a calcrete layer (often silicified or dolomitic) and as disseminated

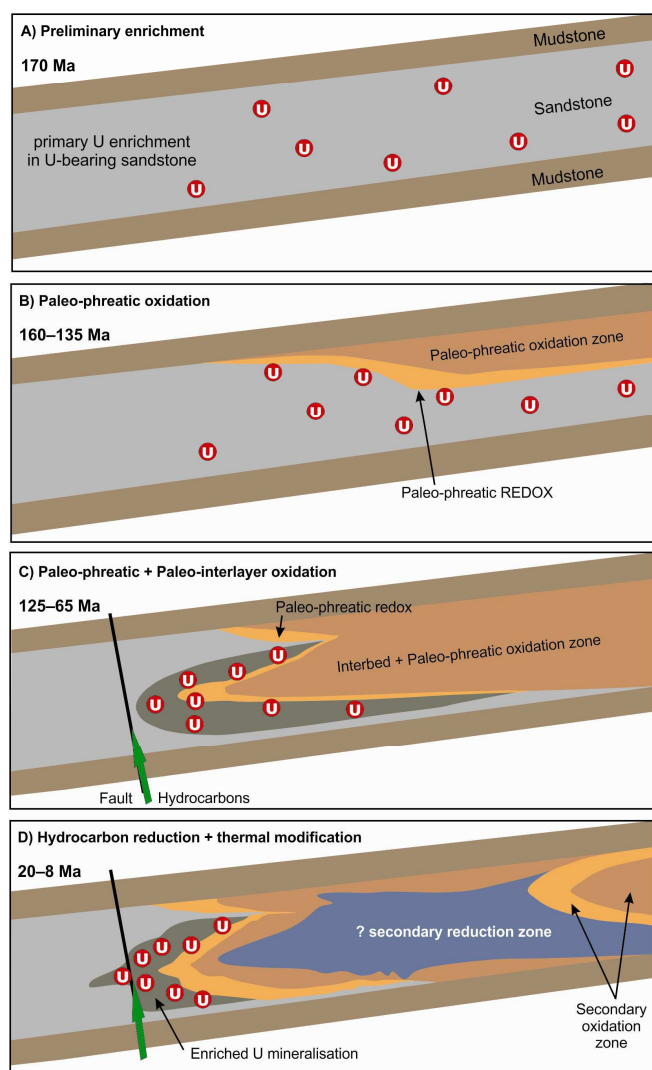


Figure 10. Roll-front mineralisation model for the Dongsheng uranium deposits, northeastern Ordos Basin, China (modified from Li et al., 2008).

- coatings on quartz grains in fine sands and on clay;
- the mineralisation depth is generally shallow, occurring between the surface and 15 m (at Yeelirrie, mineralisation extends down to 32 m below surface);
- vanadium mainly sourced from greenstone and/or granite is necessary in forming carnotite mineralisation (e.g., Wiluna, Napperby and Yeelirrie deposits), although its origin is often debated.

There is no significant calcrete-hosted uranium mineralisation reported in China to date, although there are paleovalley-related sandstone and lignite style uranium deposits in northern China.

Lignite deposits

Uranium mineralisation occurring in lignite and in clay and sandstone immediately adjacent to the lignite are known from the Serres Basin, Greece and in North and South Dakota, USA, but uranium grades are very low and average less than 0.005% U_3O_8 (McKay and Miezitis, 2001). Uranium adsorbed on carbonaceous matter is not present as discrete uranium minerals. The uranium content associated with this type of mineralisation was initially thought

Table 2. Mulga Rock - Ambassador uranium deposits. Inferred resource as of 2009 June 2010. Reported by host type using a lower cutoff of 200 ppm U_3O_8 assuming open cut mining. Ordinary Kriging Grade Estimates within Parent Cells of 200 m by 100 m by 10 m. Using Cut comb U_3O_8 Composites (combined chemical and radiometric grades) (from Coffey Mining Pty Ltd, 2010)

Host Type/Lithology	Resource Classification Inferred		
	Tonnes (Mt)	U_3O_8 Grade (ppm)	Contained Metal (Kt U_3O_8)
Upper Lignite – Lignite and carbonaceous claystone	16.7	600	10.0
Lower Lignite/ Sandstone – Mixed environment of lignite, carbonaceous sandstone and sandstone	3.7	320	1.2
Sandstone – Reduced sandstone	4.0	310	1.2
Total	24.4	510	12.5

too low to warrant commercial interest (Dahlkamp, 1993), but higher grade deposits have been reported subsequently in Australia (e.g., Mulga Rock uranium deposits, Table 2; Inwood, 2009; Macfarlane and Inwood, 2010) and China (e.g., Ordos Basin; Li et al., 2008).

The Mulga Rock deposits, comprising three separate zones of mineralisation, Shogun, Emperor and Ambassador, are situated in the western margin of the Eucla Basin, approximately 250 km east-northeast of Kalgoorlie in Western Australia (Fig. 1). The deposits are distributed along the outer margin of a broad bend in a paleovalley (Inwood, 2009). The uranium mineralisation is hosted by lignites, carbonaceous clays and sands. Highest grades, average 0.06% U_3O_8 , are in lignitic clays immediately below the redox boundary at the base of the weathered zone (Macfarlane and Inwood, 2010). The mineralised zones, averaging about 2 m thick, are flat-lying and are from 20 to 50 m below surface. The redox boundary (commonly >30m deep) presents as a sharp front between kaolinitic paludal clay and lignite and commonly approximates the present day water-table (Douglas et al., 2003). The channel sediments were deposited during middle Eocene time and are composed of three broad units (Fig. 14): (1) basal fluvial sands and gravels; (2) lacustrine to paludal sediments, including lignite, clay-rich lignite and carbonaceous sands; and (3) fluvial sands and interbedded lacustrine sediments, which are generally oxidised, ferruginised and silicified (Douglas et al., 2003).

Uranium, sourced from granitoids and metamorphics of the Yilgarn and Albany-Fraser Provinces, was transported by groundwater flowing in the paleovalley sediments and adsorbed onto the organic matter within the lignite/carbonaceous clay (Fulwood and Barwick 1990). The adsorbed uranium was remobilised by oxidising groundwater and subsequently re-adsorbed onto lignitic layers near the base of the oxidised zone. This had the effect of upgrading the initial low concentration of uranium. The grade of mineralisation and thickness are controlled by permeability and organic matter-content of the host sediments, with the highest grades and thickest zones of mineralisation developed within the more organic-rich and more permeable sediments (Macfarlane and Inwood, 2010). Oxidised sands and silts above the redox boundary are depleted in uranium relative to daughter products, whereas reduced sediments immediately below the redox boundary are enriched in uranium relative to daughter products (Fulwood and Barwick, 1990).

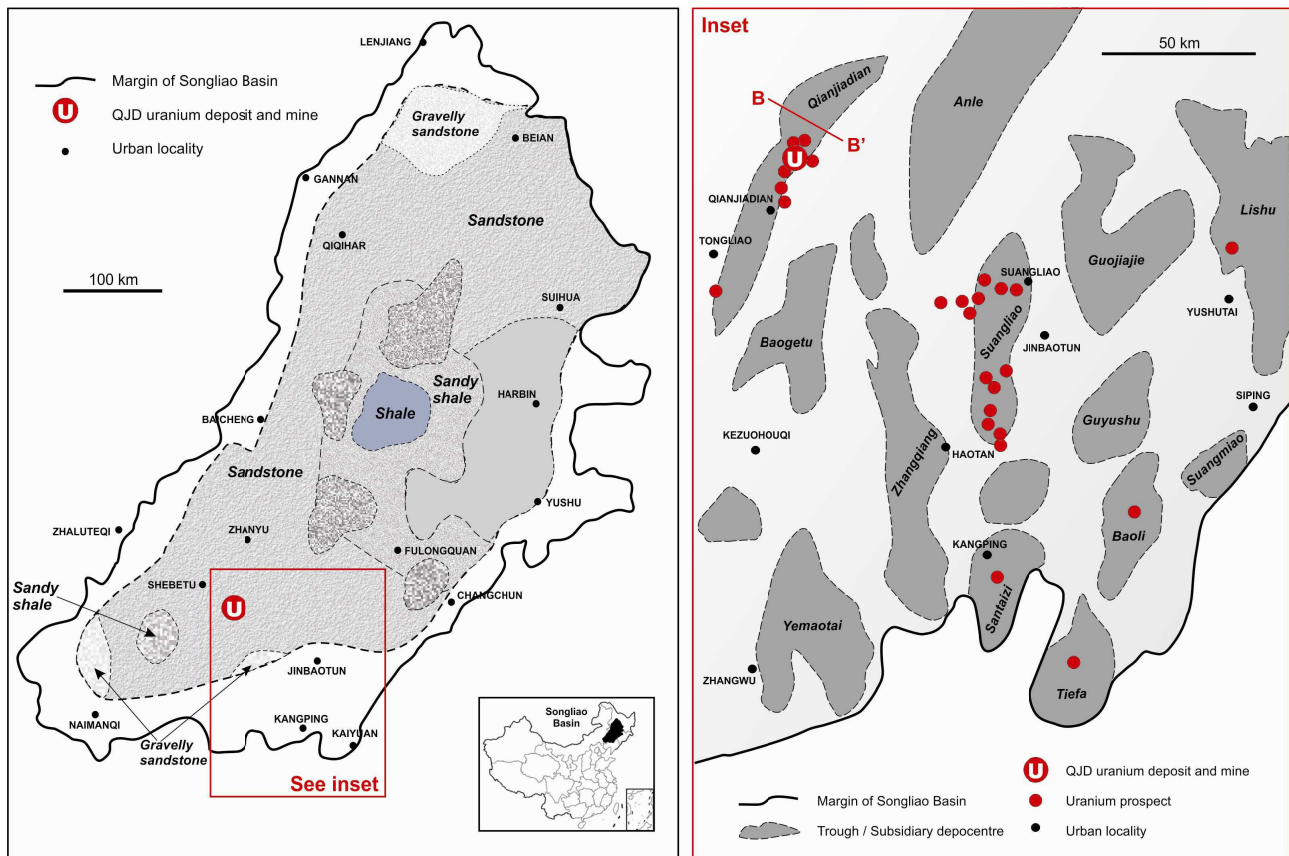


Figure 11. Major sandstone uranium deposits and prospects in subsidiary depocentres along the southern margin of the Songliao Basin, northeastern China. Qianjiadian (QJD) uranium deposits are hosted in the sandstone of the braided-fluvial Yaojia Formation (Late Cretaceous).

Three major styles of uranium mineralisation are recognised at the Ambassador deposit, Mulga Rock (Fig. 14; Macfarlane and Inwood, 2010): (1) Upper Lignite - enriched in U, REE, Ni, Co, Sc, V and locally Cu and Ag; (2) Lower Lignite and associated sandstone; also enriched in base metals; and (3) a basal sandstone hosted mineralisation. Macfarlane and Inwood (2010) considered that the metals probably migrated upwards along fault zones, through the sandstone and lignite, finally being trapped by an impervious layer lying directly above the lignite.

Characteristics of paleovalley-related uranium mineralisation

Although almost every known fluvial uranium deposit has its own distinctive characteristics, sandstone roll-front, lignite, and calcrete style mineralisation models have proven to have universal application. The key common factors of these models include uranium-rich source rocks, paleovalley networks, oxidising groundwaters and a suitably porous and reduced sediment host, or chemical and environmental conditions that favour formation and precipitation of uranium minerals (e.g., carnotite) from oxidised fluids. Large areas of stable geological provinces and cratons satisfy these criteria. The successful combination of these factors is demonstrated by the numerous uranium prospects associated with Mesozoic and/or Cenozoic paleovalleys of central and Western Australia and northern China (Fig. 1). All the uranium occurrences are in sediments of late Mesozoic to Cenozoic

age (Fig. 3) and this is in part due to the high organic content in the paleovalley sediments deposited at times of warm and wet climatic conditions with widespread colonisation by land plants (Alley and Lindsay, 1995).

The necessity for a proximal basement source of uranium to form a sandstone hosted or paleovalley-related deposit is a point of current debate, with some studies indicating that enrichment of uranium from leaching of weakly uraniferous sands within the sedimentary environment is sufficient (e.g., Songliao Basin of northern China) (Li et al., 2008). Nevertheless, the presence of spatially related uranium-rich granites (such as the Mesoproterozoic Hiltaba Suite and broad equivalents in South Australia, and Archean granitoids in the Yilgarn Craton, Western Australia) is a desirable component of the mineral system. A spatial relationship is evident between areas of high uranium in basement and uranium mineralisation within the surrounding sediments, e.g. Beverley and Four Mile deposits in close proximity to uranium-enriched granites and gneisses of the Mount Painter Inlier in the northern Curnamona Province. Paleovalleys overlying the Gawler and Yilgarn Cratons are also sourced from uraniferous basement rocks, where deeply weathered basement rocks were incised during late Mesozoic and early Cenozoic times and the sediments in these paleodrainage networks incorporate significant uranium occurrences (Figs. 1 and 2). The presence of key ingredients for uranium deposit formation, together with identified resources, make northern China and southern, western and northern parts of Australia highly prospective for paleovalley-related uranium deposits, in particular, sandstone (roll-front) styles but also surficial

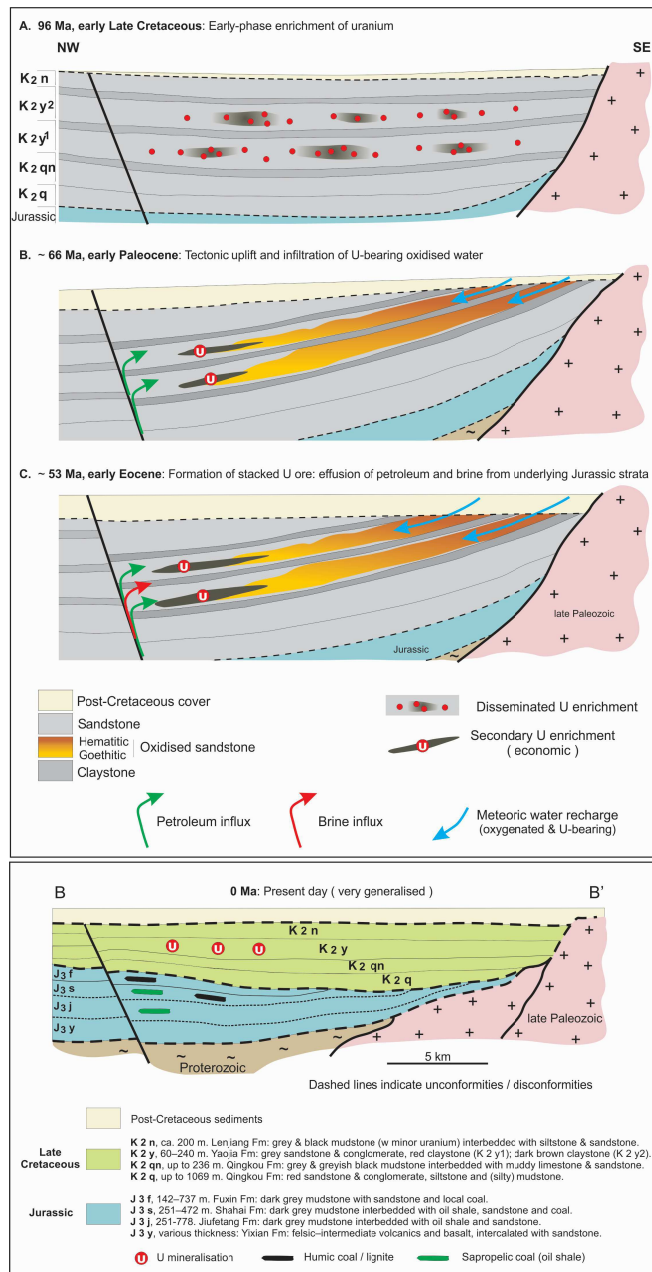


Figure 12. (a) Geological cross-section (B-B': Figure 10 inset) through the QJD uranium deposits (southern Songliao Basin, China) showing the stratigraphic position of uranium mineralisation (Cretaceous sediments) and petroleum source rocks (Jurassic strata) comprising humic and sapropelic coal); (b) Palinspastic cross-section model and mineralised model for the formation of QJD uranium deposits, Songliao Basin. Stage A: Pre-enrichment of uranium in the Yaojia Formation; Stage B: Tectonic uplifting and infiltration of U-bearing oxidised water; Stage C: Effusion of petroleum (oil + gas) and brine into Cretaceous strata.

deposits, which to date have attracted less attention as an exploration target.

Similar to other places (e.g., USA, Kazakhstan and Namibia), paleovalley-related uranium deposits in Australia and China have the following characteristics:

- Paleovalleys largely drained deeply weathered, high-uranium

source rocks. In most cases, the primary uranium source can be identified in nearby uranium-rich basement rocks which have shed sediment into the basin.

- Most occur in Mesozoic and Cenozoic sediments; a likely result of changing paleoclimatic conditions during the Mesozoic and Cenozoic with associated weathering and erosion of granitic/metamorphic provenances and subsequent supply of oxygenated solutions under arid to semi-arid climatic regimes.
- Host-rock units are alluvial/ fluvial/ lacustrine to marginal marine sediments, particularly medium to coarse grained, sometimes interbedded with conglomerate.
- Host-rock units were deposited generally in alluvial, fluvial and lacustrine environments in paleovalley-related settings, including channel, lagoon, estuarine and marginal basin.
- The host-rock units are those with good regional groundwater transmissivity. Porous sandy host-rocks are bounded by less permeable mudstone units, and are generally buried by a minimum 80 m thickness of overlying sediment, which is important for focusing oxidised U-bearing groundwaters into the sedimentary sequence with the development of redox fronts.
- Host-rock calcretes / silts are generally buried by thin sediment cover.
- Fossil carbonised plant matter or humic matter and reducing conditions in host rocks are commonly present.
- Uranium concentrations are controlled by sedimentary and diagenetic-epigenetic features but may be related indirectly to tectonic structures and basement composition that potentially modify sedimentation, groundwater flow or groundwater composition.
- Uranium is precipitated along a redox boundary [at the contacts between oxidised (altered) and reduced (non-altered) rocks] at the lateral margins of paleochannels.
- The mineralising solutions were low-temperature groundwater.
- The ore minerals are epigenetically derived from long-term weathering processes in the cratons, although diagenetic processes also have significance in controlling mobilisation and deposition.
- Mineralisation takes place generally in paleovalleys that incised low-relief cratonic regions (e.g., Gawler and Curnamona of South Australia) with low-angle basinward discharge gradients which aids in deposit preservation (e.g., Eucla Basin and Callabonna sub-basin of South Australia and Ordos and Songliao Basins of northern China). Periods of uplift are important in initiating erosion, the development of paleovalleys and downward movement of oxidising ground waters. For instance, neotectonic activity is ongoing in some regions (e.g., Beverley area of South Australia and Dongsheng area of Ordos Basin, north China) and may be a significant factor in channelling fluids along faults and/or redistribution of uranium.
- For calcrete uranium mineralisation, it is important that Cenozoic paleovalley systems drain high radiogenic enriched bedrock with anomalous vanadium content.

The genetic models proposed for paleovalley-related uranium deposits worldwide are mostly consistent in that uranium concentrations in permeable sandstone were the result of low-temperature oxidised solutions, which leached uranium from the source rocks and precipitated secondary uranium mineralisation at a

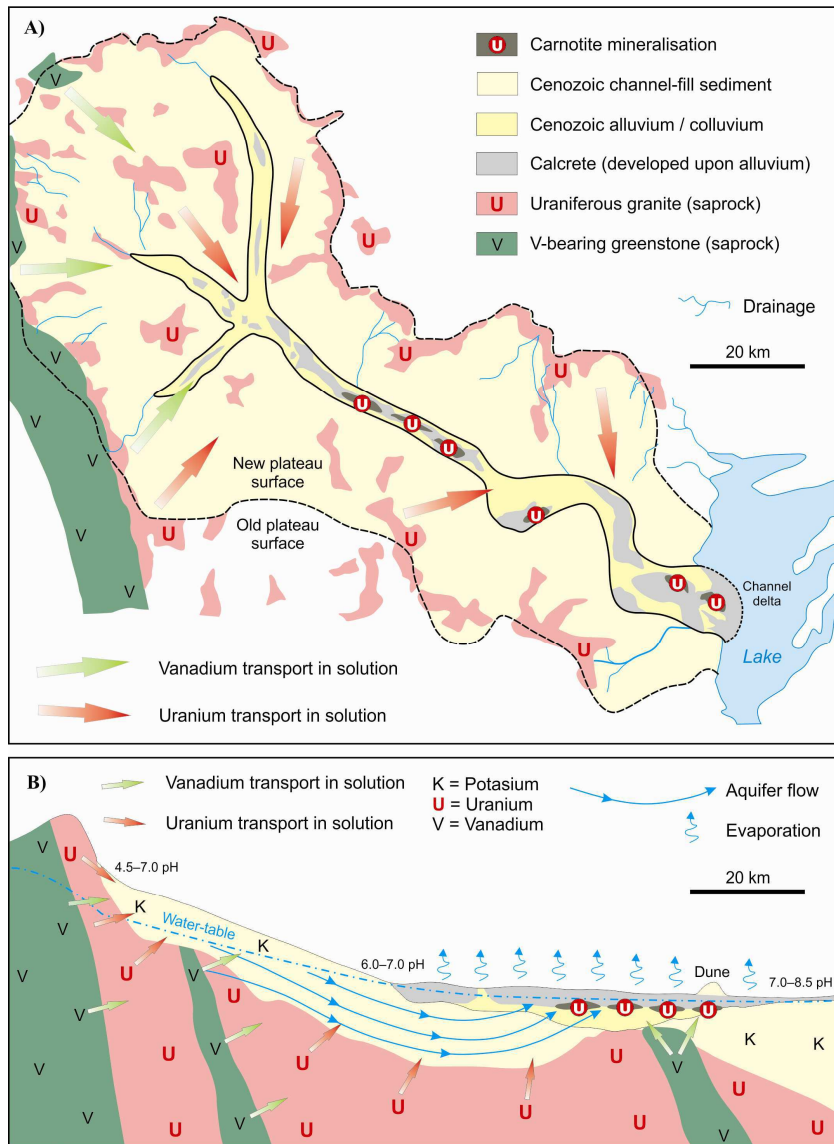


Figure 13. (a) Generalised model of valley-fill calcrete-hosted (carnotite) uranium mineralisation, based on Yeelirrie and Lake Way deposits, Western Australia (adapted from Mann and Deutscher, 1978); (b) Schematic cross-section through calcrete-hosted uranium mineralisation model, based on Yeelirrie and Lake Way deposits (after Mann & Deutscher, 1978).

chemical interface usually involving a reducing agent. These models have been applied in Australia and China at local scale with some success and there is broad consensus that considerable scope exists for ongoing discovery of paleovalley-related uranium mineralisation on a scale comparable to that discovered in Kazakhstan and USA. Variations to the models reflect local conditions and include the source of uranium, nature of the groundwater and transportation mechanisms, and type and distribution of reducing agents which affect precipitation of uranium minerals (Abzalov, 2012).

Exploration Methodology

The paleovalley systems that now host uranium mineralisation formed originally by erosion of pre-Mesozoic or pre-Cenozoic landscapes of mostly weathered crystalline basement, with incised channels and valleys subsequently infilled by fluvial, colluvial,

alluvial, lacustrine, estuarine and even marginal marine sediments accumulated during the Mesozoic or Cenozoic periods. Whilst paleovalleys have proven highly prospective for uranium in Australia and China, exploration can be problematic. One of the major difficulties associated with poorly-defined buried paleovalleys is undertaking exploration over large areas beneath substantial overburden without having to resort to costly, close-spaced drilling. Techniques that allow for precise geometric definition of paleovalleys and associated fluvial channels are therefore important in the overall effectiveness of exploration. Remote sensing, digital topography, geophysical and computer modelling techniques have proven to be useful and important tools in the delineation of paleovalleys (Hou, 2008; Hou and Mauger, 2005; Hou et al., 2001; 2003; 2007a). Knowledge and evidence from sedimentology is combined with other geological and geophysical characteristics to arrive at a general reconstruction of paleovalley architecture and history. Physical property contrasts that exist between the paleovalley sediments and the underlying bedrock can be differentiated by various geophysical methods to locate the incised-valley architecture (Hou et al., 2003). Where the physical property contrast between the paleovalley fills and the surrounding geology is poor (i.e., younger paleovalley incised into older basinal sediments, e.g., the Lake Frome region of South Australia), difficulties can arise in selecting effective methods to explore paleovalleys (Hou et al., 2007a), which are discussed below.

Integrated geoscientific datasets can contribute to an understanding of paleovalleys. The shape and depth of channels may be interpreted using combined data from topographic and digital elevation models, remote sensing imagery, magnetics, seismic, gravity, airborne and transient electromagnetics, and radiometrics. These interpretations normally require constraints and validation that may include field observations, a compendium of geological and drilling data, and computer modelling of ancient landscapes (Hou et al., 2003; 2007b). Successful procedures can be developed for defining paleovalleys by combining imagery, geological, and geophysical data, with broader understanding of continental sedimentary processes and paleoclimatic history of a region to constrain architectural and evolutionary models of channel development (Hou et al., 2001).

Exploration for paleovalley-related uranium deposits has traditionally focused on defining paleovalleys and changes in a channel's course resulting in a reduction of channel flow, with consequent accumulation of organic matter (reducing material) and build up of medium to coarse-grained sediments (point bar and overbank? deposits). Other targets include channel confluences that provide an opportunity for mixing of fluids with different oxidation potential (Eh). Techniques have been developed to define channel morphology even where buried by over a hundred metres of exotic cover sediment (e.g. AEM, remote sensing; Hou and Mauger, 2005; Hou et al., 2001, 2003).

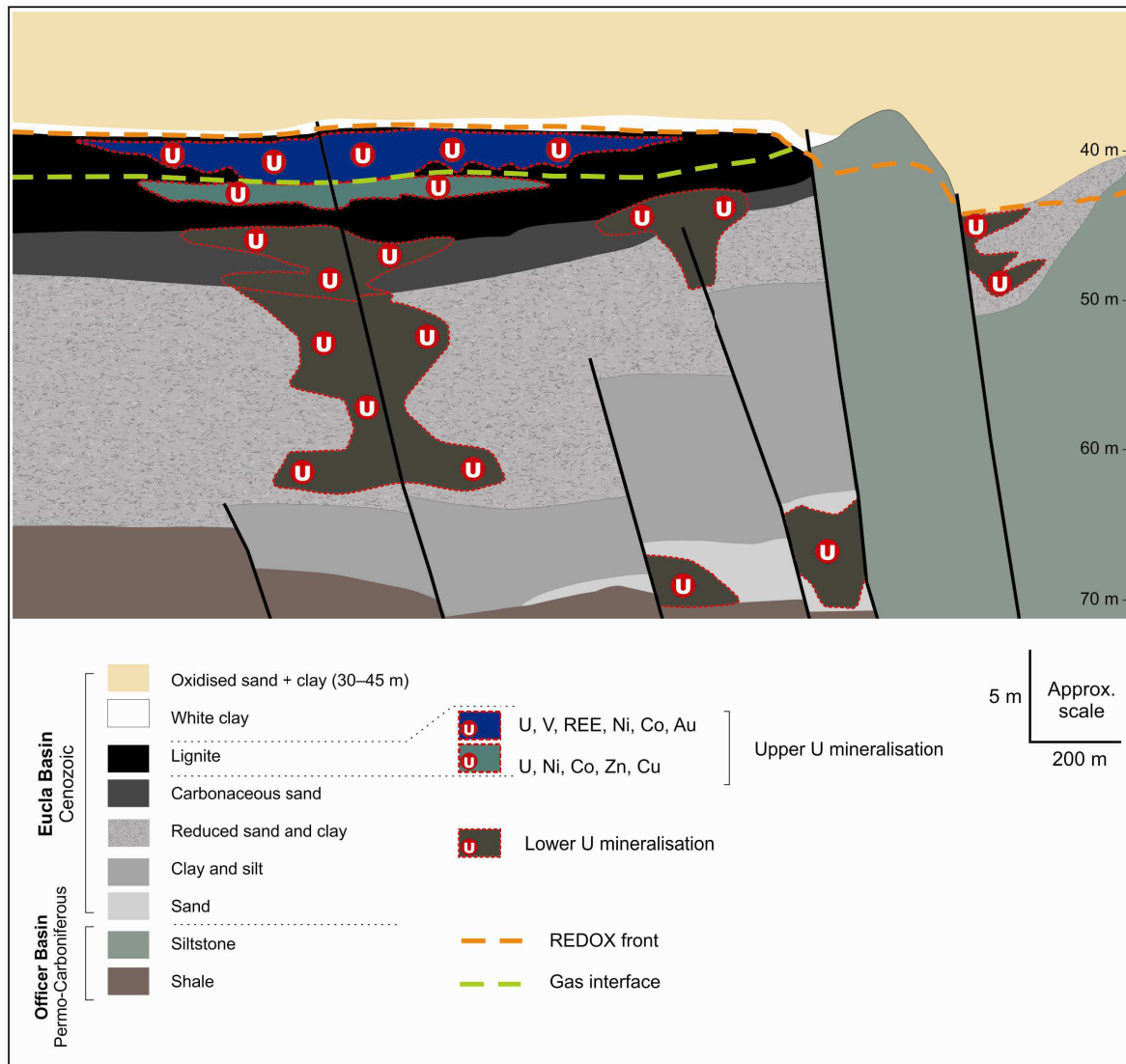


Figure 14. Geological cross-section through Mulga Rock uranium deposit (modified from Inwood, N., 2009).

Paleovalley mapping

A map of paleodrainage and Cenozoic coastal barriers of South Australia was released by Geological Survey of South Australia in 2007 (Hou et al., 2007a), and upgraded in a second edition (Hou et al., 2012), available in hardcopy and GIS. It is most useful in the conceptual stage of exploration programs. The thematic map includes time-scaled paleovalleys, paleocoastal barriers and strandlines, together with known mineral occurrences, in particular uranium and heavy minerals. When used in combination with other spatial layers, in particular geology and geophysics, the ‘essential ingredients’ for a particular uranium mineralisation model can be compared and evaluated in order to identify areas with potential to host uranium. In most cases, additional techniques will be required to define the detail of the paleodrainage.

Remote sensing imagery

While a **Digital Elevation Model (DEM)** may not directly show the distribution of paleovalley landforms, it can provide indirect associations related to links between modern and ancient (e.g.,

Palaeogene) landscapes, because modern drainages usually erode relative soft zones and are often related to previous paleovalleys. With increasing resolution, the detail of interpretation will usually increase. However, the regional-scale interpretation of paleovalleys may be complicated by too much detailed information derived from high resolution DEMs. Processed **Landsat TM** satellite imagery is useful for regolith-landform mapping, particularly when draped over a DEM to enhance terrain visualization, which can be influenced by types of paleochannel sedimentation (e.g., channel silcrete accumulated along the Tallaringa paleodrainage system of South Australia). These maps can be used to identify paleovalleys where the paleochannel has an influence on surface features and regolith materials (e.g., vegetation association, arrangement of playa lakes, alluvial terraces, silicification). Compared to Landsat imagery (7 bands), **ASTER and Hyperspectral Remote Sensing** contain more spectral bands (14 and >100 bands respectively) which can potentially distinguish most surficial features related to paleovalley sediments. The detector and orbital configuration of **NOAA-AVHRR** and **ASTER** night-time satellites provide thermal data that are potentially useful for detecting temperature variations in subsurface sediments related to the elevated moisture content of the channel (e.g., Hou and Mauger, 2005).

Thermal data can therefore be used as a quick and inexpensive method for mapping paleovalley sediments, particularly when used in conjunction with other (e.g., geophysical) data sets and preferably with some drill hole or geological control.

Geophysical methods

Paleovalley **magnetic** (either positive or negative) anomalies may be defined if high resolution surveys are used and if there are sufficient magnetic minerals in the channels or measurable magnetic contrast between the channel sediments and bedrock. Mesozoic and/or Cenozoic paleovalleys are not usually visible on regional magnetic data, as they are relatively shallow features, but careful use of detailed survey data may assist in locating channel deposits (e.g., basalt flows buried within the paleovalley generally showing a positive magnetic anomaly). **Gravity** anomalies in the earth's gravitational field can in some cases be used to define the thickness and extent of the fluvial sediments, and hence paleovalleys, due to the contrast in density between the sediments (e.g., sand and clay having a density of around 1.8g/cc; Berkman, 1995) and fresh bedrock (e.g., granitic basement having a density of 2.7 g/cc; Berkman, 1995). **Radiometric** data is not a mapping tool for buried paleovalleys, but is effective in linking physical dispersion of sediment with uranium-rich source regions, especially when overlain on DEM, Landsat, NOAA, or AEM images. Surficial uranium deposits associated with calcrete in paleodrainage sediments have been successfully delineated using airborne radiometrics, due to localised, high uranium counts (e.g., Wilford et al., 2009).

Electromagnetic (AEM and TEM) methods measure the electrical conductivity of the ground both laterally and vertically. The data can be processed to show ground conductivity as a function of depth and can thus define channel sediments due to their porosity, moisture content and the conductivity of the groundwater within them. This technique has been used successfully in South Australia for paleovalley identification, e.g., Garford paleovalley and Kingoonya paleovalley. The technique however, is problematic for application in places where channel sediment fill is incised into basinal sediments because of similar conductive features between channel and basin sediments, such as Callabonna Sub-basin, South Australia. Regional AEM data over the Callabonna Sub-basin, however, have been effective in mapping fault displacement of paleovalley sediments and in identifying areas where groundwaters of differing salinities interact, both of which appear to be significant local factors influencing uranium deposition (Michaelsen et al., 2012). Shallow **seismic** reflection and refraction imaging can be used for investigating subsurface structure (particularly in sedimentary terrains) and therefore have application for delineating paleovalleys. By integrating reflection and refraction techniques, it is possible to determine paleovalley depths, variability of materials, and the morphologies of both shallow and deeper strata (Drummond, 2002). The **Ground penetrating radar (GPR)** method is useful for delineating the geometry, structure and thickness of channel deposits by providing a high-resolution image of subsurface features in the form of a cross-section view. However, this technique is only suitable for shallow investigation (up to tens of metres in ideal conditions).

Structural and basement geology

Basement structure and lithology may be important in controlling

channel morphology, and ultimately the location of uranium mineralisation. Holbrook and Schumm (1999) showed that an increase in slope along the course of a channel, commonly related to uplift, would result in increased sinuosity. The Honeymoon uranium deposit of South Australia is located at a pronounced bend in the host Yarramba paleovalley, where gravity and magnetic imagery indicate a fault cross-cutting the channel (Southern Cross Resources Australia Pty Ltd., 2000). Here, the channel has more deeply incised the underlying basement rocks at a point which corresponds to a regional-scale redox interface within the basement lithologies.

Sedimentological analysis

Sedimentological data and interpretation, when combined with other geological and geophysical information can be used to provide a general reconstruction of the paleovalley architecture and history (Hou and Mauger, 2005). Knowledge of the stratigraphic and geographic evolution of the area is necessary to interpret the regional depositional, environmental and paleogeographic framework (Hou, 2008). Sequence stratigraphic methods, supplemented by studies in paleoclimate, mineralogy, petrology and geochemistry of the sediments have proved useful in studies on the Gawler Craton of South Australia (Hou et al., 2001; 2003).

3D Computer modelling

Where sufficient data are available, 3D visualisation models of the paleovalley landform can provide crucial insights into the landscape evolution and controls on the dynamics of paleorivers. The paleovalleys interpreted from GIS and geophysical datasets can be viewed either as 3D plume diagrams, mapped onto surfaces, or as slices, such as the paleovalley and paleolandscape with exploded layers separating variously aged paleosurfaces (Hou, 2008; Hou et al., 2004).

Location, definition and assessment of mineralisation

While groundwater geochemistry for uranium in solution usually gives misleading results, multi-element data from a limited number of boreholes can be used to distinguish prospective sediments by taking into account pH, equilibrium with carbonate minerals, and carbonaceous matter content (Giblin, 1987). The delineation of paleovalley-related uranium by surface geochemical methods is not well established over known uranium districts in Australia or China, particularly for deeply buried deposits. No successful methods have been reported to date. Elsewhere, techniques that have been used with some success include gas methods (GVP, radon), soil sampling (shallow deposits) and CHIM (electrogeochemical) methods (Fabris et al., 2006; Luo et al., 2004, 2006).

Many prospective paleovalleys containing oxidised and reduced sands with uranium at redox interfaces have been identified within regions of South Australia (Fig. 2). **Test drilling** is required to check and refine the paleovalley interpretation (Hou, 2008; Hou et al., 2003). Drillhole data need to be continually updated to refine and improve the detail of paleovalley mapping. In the Gawler Craton of South Australia, spectral logging of samples using PIMA II (Portable Infrared Mineral Analyser) has been useful in providing a consistent independent means of identifying paleosurfaces for input into 3D

paleovalley models (Hou and Mauger, 2005). Drilling in paleovalleys with relatively unconsolidated sediments mainly include mud rotary and RC percussion with air core, or sonic drilling to recover core. Gamma and Prompt Fission Neutron (PFN) logging are widely used to estimate the grade of *in situ* uranium mineralisation and the state of radioactive disequilibrium, with chemical analysis used on relatively few samples, primarily to confirm uranium grade in probable ore zones and to establish calibration for PFN and gamma logging (Penney, 2012). Down-hole geophysical logs in combination with visual logging of drill samples, provide the main inputs for sedimentary facies analysis and reconstruction of paleovalley architecture to model the uranium distribution and sedimentological constraints on mineralisation. All of these aim at improving the understanding of facies and micro-environment, potential paleo-redox fronts and mineralisation processes occurring within paleovalley systems. These data are used to develop predictive models of paleovalley-hosted uranium systems with the intention of reducing exploration costs.

Discussion and conclusion

In Australia and China, extensive emplacement of uranium-enriched felsic igneous rocks, particularly during Precambrian time, provide a widespread source of uranium that has been remobilised over geological time and concentrated into economic deposits. These include magmatic-related deposits, such as Crocker Well, and hybrid-related deposits throughout the Olympic Domain in Australia that formed during, or shortly after, the time of emplacement (Fig. 2). Uranium deposits within paleovalley and associated sediments and associated continental basins and marginal marine environments occurred throughout the Phanerozoic but most particularly during Mesozoic and Cenozoic times. The felsic igneous rocks, particularly of Precambrian age, tend to be highly fractionated with alkaline affinities, and are interpreted to provide the source of uranium for deposits occurring at sites in Australia and China. Mineralisation in magmatic-related deposits, such as Crocker Well, and hybrid-related deposits throughout the Olympic Domain of Australia is interpreted to be of a similar age to these felsic igneous activities (Fig. 2). The Honeymoon-type granite of South Australia, for instance, is interpreted as the source of mineralisation for the paleovalley-hosted Honeymoon uranium deposit. This association highlights potential exploration targets in the southern Lake Eyre Basin of South Australia (Fricke and Reid, 2009).

Paleovalley-related uranium deposits contain significant uranium resources in Australia and China. They occur in sedimentary marginal basins and their peripheral paleovalleys ranging in age from Carboniferous to Cenozoic. Basin- and channel- and surface-related uranium mineral systems are well represented throughout western, southern and northern Australia and northern China. Mesozoic and Cenozoic paleovalleys in close proximity to uranium-enriched granites have repeatedly demonstrated a high level of prospectivity throughout these regions. Known paleovalley-related deposits occur in these regions, where mineralisation is interpreted to have been sourced from uranium-enriched igneous rocks and basinal sedimentary rocks. Given the spatial proximity to the known source rocks, potential exists for the discovery of additional paleovalley-related uranium deposits in these regions. In the northern Curnamona Province of South Australia, for example, the highly uraniferous rocks of the Mount Painter and Mount Babbage Inliers provide a source for paleovalley-related deposits such as Beverley, Four Mile, and Pepegooona to the east of

the inliers. Therefore, similar sedimentary sequences that flank the inliers to the north and west have potential for paleovalley-related deposits and are a focus of ongoing uranium exploration activity. Recent work by Skirrow (2009) and Hore and Hill (2009) highlight the potential also for sediments of Mesozoic age to host uranium mineralisation in these regions of South Australia.

Paleovalley-related uranium models are important for exploration as they can be used to integrate a wide variety of potentially significant geological factors leading to the formation of deposits. Improved understanding of geological controls and landscape history can assist with target definition and choice of technique when mapping paleovalley distribution. Regional exploration for paleovalley-related uranium deposits can be based initially on empirical data gained from known deposits. Models will evolve as additional data are gathered during exploration and from on-going sedimentological studies. Exploration should begin with the delineation of paleodrainage by the examination of a combination of inexpensive surface and remotely sensed data (e.g., available geological mapping, DEMs, airborne radiometric, Landsat TM, NOAA, ASTER, night-time thermal images) and compared in GIS. The model can then be progressed using geophysical techniques (e.g., AEM and/or TEM) and drilling. The ultimate aim is to construct 3D geological representations in which the sedimentary facies and depositional patterns can be mapped; alteration and facies trends traced; structural features identified; and finally the mineralising system outlined and evaluated.

Mesozoic and Cenozoic organic-rich sand, clay, calcrete and lignite are hosts for sandstone, calcrete and lignite uranium deposits in the regions/areas where paleovalleys have developed and are a focus for ongoing and successful uranium exploration in both Australia and China. However, geological settings similar to that of the Chusarysu and Syrdarya Basins of southern Kazakhstan (e.g., Aubakirov, 1998; Bykadorov et al., 2003) and Songliao and Ordos Basins of northern China (e.g., Huang et al., 2005; Li et al., 2008) can probably be identified in a number of hydrocarbon-bearing basins in Australia, such as the hydrocarbon or H₂S-rich Cooper Basin underlying several organic-poor sandstone aquifers in the Eromanga Basin of Australia (Jaireth et al., 2008).

In summary, based on current models for paleovalley-related uranium deposits, and the widespread distribution of uranium-enriched sources, we conclude there is considerable potential for further discovery of economically significant, paleovalley-related uranium deposits in Australia and China, particularly in the following areas:

- (Cenozoic) Lake Eyre Basin, particularly in the areas in proximity to Mt Painter and Peake and Denison inliers of South Australia,
- (Mesozoic) Eromanga Basin (particularly Eromanga margins) and paleovalleys,
- (Cenozoic) Eucla Basin and paleovalleys of southern Australia,
- (Cenozoic) Pirie Basin and paleovalleys of South Australia,
- (Cenozoic) Paleovalleys that drain the Yilgarn Craton of Western Australia,
- (Cenozoic) Ngalia Basin and paleovalleys of central Australia,
- (Mesozoic) Ordos and Songliao basins and paleovalleys in China,
- (Cenozoic and Mesozoic) Frome Embayment (particularly Eromanga margin) of South Australia.

Australia and China remain highly prospective for the discovery of new paleovalley-related uranium deposits, with night-time thermal imagery (e.g. NOAA, Landsat TM7 and ASTER) of remote sensing data and regional airborne geophysical surveys likely to be of

assistance in defining paleovalley systems that drained uranium rich source rocks and may host uranium.

Acknowledgements

This paper has benefited from various discussions with industry (e.g., Toro Energy Ltd, Heathgate Resources Pty Ltd, Red Metal Limited, Coffey Mining, Southern Cross) and with international researchers (e.g., from USA, Canada, Russia, Kazakhstan, India, and China) through IGCP-514. We gratefully acknowledge the support and enthusiasm of IUGS and UNESCO who funded the project via the IGCP scheme, providing opportunity for many individuals to be involved in the project events. We also very much thank all the organisations, associations and mining companies which provided IGCP-514 with additional financial support – especially those which kindly hosted or sponsored our field trips and project publications, or underwrote IGCP-514 events. We are also grateful for the advice and discussions of Australian and Chinese geoscientists, especially Roger Fidler, Mark McGeough, Steve Hore, Tania Wilson, Alan Mauger, Laszlo Katona, David Gray, Jindai Zhang, and Xianrong Luo on various aspects of uranium geochemistry and the application of remote sensing, geochemical, geophysical and GIS techniques. An early version of the paper was improved following helpful comments from Professor Larry Frakes and careful review by P. S. Parihar.

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Baohong Hou received his degrees of B.Sc. in 1982 and M.Sc. in 1985 from Jilin University in China. He went on to complete his Ph.D. at the University of Adelaide, Australia in 1994. He is a Senior Principal Geoscientist of the Geological Survey of South Australia and an Adjunct Professor at Jilin University. His research interests span a range of topics within ore deposit geology.



Ziying LI, Ph.D. in Geology at the Technical University of Berlin/Germany in 1996. He now works as President, Professor in the Beijing Research Institute of Uranium Geology. He is vice president of The International Association on the Genesis of Ore Deposits (IAGOD). His main research interests focus on mineral deposits geology and exploration. He has published over 120 books and papers



John Keeling is Senior Principal Geologist and Team Leader of the Mineral Systems Team with the Geological Survey of South Australia. His qualifications include a BSc in geology (University of South Australia) and MSc in industrial mineralogy (University of Hull, UK). He has over 30 years experience in applied geoscience research, mostly in non-metallic and industrial minerals.



Adrian Fabris graduated from the University of Adelaide with Honours in 2000. Since joining the Geological Survey of South Australia he has worked on projects related to regolith geoscience and exploration geochemistry throughout South Australia and on commodities such as heavy mineral sands, uranium, base metals and iron-oxide-copper-gold deposits.